Public Interest Energy Research (PIER) Program
FINAL PROJECT REPORT

Pulsed Flow Guidelines: Managing the Annual Snowmelt Hydrograph and Winter Floods in Regulated Boulder-Bedrock Sierra Nevada Rivers

Prepared for: California Energy Commission
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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

- PIER funding efforts are focused on the following RD&D program areas:
- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Pulsed Flow Guidelines: Managing the Annual Snowmelt Hydrograph and Winter Floods in Regulated Boulder-Bedrock Sierra Nevada Rivers is the final report for the Management of Ecological Evaluation of Hydropower Pulsed and Manufactured Flow Releases in California's Stream Systems Project (contract number 500-01-044) conducted by McBain and Trush, Inc. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

Table of Contents

List of Figures

List of Tables

Abstract

In the Sierra Nevada, alteration of natural flow regimes by hydropower operation has contributed to the deterioration of aquatic and riparian habitats. A practical ecological management strategy recognizes that the annual snowmelt hydrograph and winter floods are dominant components of the natural hydrograph that sustain native river ecosystems. The purpose of this project is to investigate the linkage between flood and snowmelt flows and aquatic habitat in steep boulder-bedrock Sierra Nevada rivers and to develop guidelines for managing the timing and magnitude of such flows to help restore and sustain aquatic ecosystems on regulated rivers in California. These guidelines are needed because missing from many regulated Sierra rivers is a peak runoff event generated by late spring to early summer snowmelt. While snowmelt runoff floods are highly dependable annual events that accomplish most 'routine' physical work - scouring depositional features, transporting fine/coarse sediment, and building floodplains – these flows are also biologically fundamental to sustaining river ecosystems.

The study was conducted on the Clavey River, a tributary to the Tuolumne River on the western slope of the Sierra Nevada. The study quantified flood flows necessary to mobilize channel depositional features and link these processes to the availability of fish, amphibian, benthic macroinvertebrate and woody riparian vegetation habitat

Recommended pulse flow guidelines for hydropower projects located in the snow/rainfall transition zone of large Sierra Nevada river watersheds are: (1) maintain the magnitude and frequency of unregulated 3-year to 15-year winter flood peaks, (2) Divert the rising limb, peak, and fast recession limb of the unregulated annual snowmelt hydrograph using a fixed percentage of the unregulated streamflow without significantly impairing the reference condition that emphasizes woody riparian initiation and early-establishment, as well as sensitive life stages of selected fish, amphibians, and benthic macroinvertebrates. Preliminary analyses suggest maximum fixed daily diversion rates of 25 percent to 35 percent, and (3) do not divert past the annual snowmelt hydrograph recession node, the streamflow transition from the fast snowmelt recession limb to the slow snowmelt recession limb. These guidelines provide a way to prioritize existing dam operations that might have the infrastructure to promote recovery of native Sierra Nevada river ecosystems. Small capacity reservoirs capable of passing winter flood peaks up to the 15-year flood would have high priority.

While there are many demands on any given operation, the goal of recovering native river ecosystems should be done in places with the best chance of success. A next step is to apply the pulse flow guidelines to several existing and hypothetical dam operations to evaluate impacts on hydropower generation and dependable water supply.

Keywords: Snowmelt hydrograph, snow hydrology, boulder-bedrock rivers, expert habitat mapping, nested depositional features, pulse flows, annual habigraph, pulse flow guidelines

EXECUTIVE SUMMARY

Introduction

In the Sierra Nevada, dams and diversions are important causes of aquatic and riparian condition deterioration (Davis: University of California 1996). Given the number of Sierra Nevada dams and diversions and the magnitude of their impacts on river ecosystem health, a methodology is needed that can identify the timing and magnitude of instream flow releases that are affordable and capable of generating a reliable energy supply, yet still promote some acceptable level of river ecosystem health.

Purpose

The purpose of this study is to apply such a methodology to the Clavey River, a boulder-bedrock stream located in the Sierra Nevada, and to determine whether the methodology is feasible.

Project Objectives

The Project objectives were to: (1) quantify mobilization thresholds for depositional features, and establish trends in species habitat availability that are dependent on: (a) the annual snowmelt flow regime, and (b) winter peak floods; (2) as represented by the annual snowmelt hydrograph's components, assess how altering flows could directly and indirectly affect habitat used by Species of Concern; (3) demonstrate that: (a) variable winter and snowmelt pulse releases can recreate and maintain specific geomorphic and ecological thresholds, and (b) if one impounds flow such that annual snowmelt flows and winter peak floods are altered or eliminated, then geomorphic and ecological responses can be forecasted; and (4) given the results of these demonstrations, formulate example pulse flow guidelines, evaluate uncertainties in the Project's outcomes, recommend changes in the methodology, and identify further information needed.

Project Outcomes

Hydrologic, geomorphic, and biological data were compiled and analyzed. Typical analytical hydrologic curves were generated for the Clavey River and Cherry Creek. Geomorphic analyses included bed mobility modeling, field observations, and examination of paired ground and aerial photographs. From these analyses, flow thresholds for mobilizing specific depositional features were associated with annual maximum flood recurrences. Biological information was collected through expert habitat mapping and literature reviews.

Once the hydrologic, geomorphic, and biologic characteristics were determined, the synthesis methodology could be started. The methodology is largely graphical. The expert habitat mapping allowed generation of habitat rating curves; when combined with a snowmelt hydrograph, an *available habitat area* curve can be generated. Additional ecological information such as species life stage windows, species temperature thresholds, and water temperature are then added to the available habitat area curve, creating an *annual habigraph*. Considering the intersection of all data, the *ecologically available habitat area* and the number of days it is available can be estimated. In an unregulated environment, that number of days can be considered a *reference condition*; the management goal would be to optimize the reference condition, while balancing the need for water diversion.

Once all data and analyses were synthesized, the following observations and implications are noted:
The inter-annual migration of a 70°F temperature isotherm up and down the mainstem (the *trombone effect*) depends on the runoff year, and loosely follows the dominance between cold and warm water aquatic species. Therefore the magnitude, duration, rate, and timing of slow recession flows are important in benefiting either cold or warm water species. In regulated rivers, instead of creating additional rainbow trout habitat, releasing higher than natural summer base-flows could de-stratify (mix) thermal refugia.
The annual snowmelt peak and recession flows had a smaller role in geomorphic processes than initially anticipated. Winter floods perform most geomorphic work in the boulder-bedrock Clavey River mainstem. The inter-annual variation of winter peak floods is what maintains a dynamic balance of nested hydraulic controls; this balance ultimately controls small- and large-scale depositional features.

One of the primary biological implications is that variation in water year types is required if a river is to support a variety of species. This goal of desired and required variations in pulse flow releases is not the apparent goal in most reservoir release programs. For rainbow trout, California roach, foothill yellow-legged frogs, western toad, Pacific tree frog, and benthic macroinvertebrates in the Clavey River, ecologically available habitat area depends on the annual snowmelt hydrograph's magnitude, duration, timing, and rate. No one runoff year remotely approached providing ideal, or even good, habitat conditions for all species examined.

Reference conditions were defined and used to formulate example pulse flow guidelines; this approach differs fundamentally from the classical PHABSIM approach. While using the same basic habitat rating and availability curves, no optimal streamflow concept (the streamflow with the greatest habitat abundance) drives the analysis. Instead, a range of streamflows supplying abundant habitat is established by the Project biologists (and/or by a sub-group of peer biologists) from the habitat rating curves.
Readers are cautioned that these results have general application but should not be specifically applied to other Sierra boulder-bedrock rivers without similar and more detailed study. Examples pulse flow guidelines are:
No. 1: Maintain the natural frequency and timing of unregulated 3-yr winter flood peaks up to the unregulated 15-yr winter flood peaks. Most will be short duration winter floods, but a few should be longer duration rainfall/snowmelt peaks in late-winter or early-spring. More than one flood peak can occur annually.

No. 2: Divert flows represented by the unregulated snowmelt hydrograph's rising limb, peak, and fast recession limb, using a fixed percentage of the unregulated streamflow that does not significantly impair the reference condition. This study's preliminary analyses suggest maximum fixed daily diversion rates of 25% to 35%.
No. 3: Do not divert those flows represented by the unregulated snowmelt hydrograph's slow snowmelt recession limb.

Conclusions

The Project outcomes met each project objective. The example pulse flow guidelines indicate that this methodology is feasible and that quantitative detail is possible.

Recommendations

Water temperature should be given greater emphasis when evaluating instream flows. The up- and downstream movement of flow isotherms (the trombone effect) changes with water year type and timing and magnitude of flow releases. These aspects of water quality, rather than the almost exclusionary focus on habitat availability or abundance, have not been given sufficient weight in evaluating instream flows.
This methodology should be applied to several existing and theoretical dam operations. Forecasting the probable outcome of only partially satisfying the three example pulse flow guidelines should also be investigated.
A network of photographic points or sites should be initiated, with specific purposes and hypotheses explicitly stated for each photo-point location. The temptation to first invest in hydraulic modeling and bed mobility prediction should be resisted, because existing photographic evidence contradicted the study's modeling results. A more theoretical approach would require more time, would undoubtedly cost more, and would still require verification with photographs.

Benefits to California

The Project provides a successful preliminary test of a methodology for formulating quantitative pulse flow guidelines, which can promote recovery of native Sierra Nevada river ecosystems. The Project demonstrates that flushing flows will not maintain a variable mainstem channel architecture or diverse aquatic species.

Unless otherwise indicated, all pictures and graphs in this report are the outcome of the research described herein.

1.0 Introduction

1.1. Background and Overview

Although numerous studies have attempted to describe and quantify linkages between flow regime and ecological function in alluvial rivers (e.g., Williams and Wolman 1984; Collier et al. 1996; Ligon et al. 1995; Ward and Stanford 1995; Nilsson and Svedmark 2002; USFWS and HVT 1999), few have focused on steep boulder-bedrock rivers. Of the research that has been performed on boulder-bedrock rivers, much has been focused on management of a single charismatic species, rather than on the ecosystem. As a result, for boulder-bedrock river ecosystems, few tools are available for prescribing management options that will protect these river ecosystems below dams.

In the Sierra Nevada, an assessment of ecological conditions determined that three major conditions drive deterioration of aquatic and riparian ecosystems; of the three, dams and diversions that change flow timing and quantity are important (Centers for Water and Wildland Resources 1996). Given the number of dams and diversions in the Sierra Nevada, and the magnitude of their effects on ecosystem health, tools are needed to identify the timing and magnitude of flow releases that will promote river ecosystem health. To develop such tools, it is important to quantitatively understand how natural streamflows: (1) drive ecosystem functions, and (2) sustain native plant and animal species, in boulder-bedrock Sierra Nevada rivers. With this quantitative knowledge, scientists and managers can recommend flow release schedules that will better recover and protect boulder-bedrock Sierra Nevada river ecosystems.

The Clavey River and Cherry Creek provide an opportunity to compare unregulated and regulated boulder-bedrock rivers. Both are tributaries to the Tuolumne River and drain similarly sized watersheds at similar elevations. The Clavey River is the longest undammed river in the Sierra Nevada and one of California's most pristine (Moyle et al. 1996). Unlike most Sierra Nevada rivers, the Clavey is free of introduced fishes and may be the one river in the Sierra Nevada supporting only native fishes (Moyle et al. 1996). The Clavey also supports a good representation of native amphibians (Moyle et al. 1996). Cherry Creek, in contrast, has been regulated since 1956 by Cherry Valley Dam, a component of San Francisco's Hetch Hetchy water supply and power generation system. Dam operations have reduced average spring (April to June) flow by 90%, from 1045 cubic feet per second (cfs) pre-dam (1910 to 1955) to 93 cfs post-dam (1957 to 2004).

To support research toward developing environmentally safe, affordable, and reliable energy supply, the California Energy Commission formed the Public Interest Energy Research (PIER) Program. PIER hydropower research efforts are aimed at: (1) identifying gaps in understanding of hydropower and aquatic ecosystems, (2) prioritizing research needs, and (3) developing *roadmaps* to guide research on fish passage, water quality, and instream flows (California Energy Commission 2003). The PIER Program's current research focus is to assess the effects of pulsed and ramped flows on aquatic species and habitats.

In the Clavey River, the role of the snowmelt hydrograph was first investigated by the Institute for River Ecosystems at Humboldt State University (1994). A set of attributes for boulder-bedrock Sierra Nevada rivers was proposed, paralleling a similar set of attributes for alluvial rivers. Attributes are defined as "…a minimum checklist of critical geomorphic and ecological processes derived from field observation and experimentation, a set of hypotheses to chart and evaluate strategies for restoring and preserving alluvial river ecosystems." (Trush et al. 2000). In 2000, the United States Forest Service's Stream Systems Technology Center in Ft. Collins, Colorado, funded a revisit to the Clavey River; in summer 2002, Smokey Pittman collected insightful field notes and photographs of the Clavey River in 2002. By 2004, the boulder-bedrock attributes were summarized in a publication by the United States Forest Service (USFS) Systems Technology Center (McBain and Trush 2004).

1.1.1. Attributes of Steep Boulder-Bedrock Sierra River Ecosystems

To define a common vision of the characteristics of unregulated steep, boulder-bedrock rivers, important characteristics or endpoints of any management strategy must be agreed upon. Seven characteristics, or attributes, of unregulated, steep, boulder-bedrock rivers have been described elsewhere (McBain and Trush 2004) and are reproduced in Appendix A. For convenience, these attributes are summarized below.

Attribute 1. Steep boulder-bedrock Sierra Nevada rivers exhibit nested depositional features. Boulder-bedrock channels exhibit many depositional features. Examples of large, geomorphically derived hydraulic controls include valley width constrictions or expansions, and resistant bedrock outcrops. These large hydraulic controls define the overall limit to which coarse sediment can be deposited in each bedrock channel segment. These large hydraulic controls induce coarse depositional features that in turn perform as smaller hydraulic controls inducing finer secondary depositional features. Examples of hydraulic controls that can function on large and small scales are transverse boulder "ribs;" they are prominent, self-formed, depositional features common in bedrock Sierra Nevada rivers that function as hydraulic controls for diverse secondary, and even tertiary, depositional features. Smaller hydraulic controls within larger hydraulic controls results in a complex, nested, depositional channel morphology that provides rich aquatic and riparian habitats (McBain and Trush 2004).

One large, geomorphically-derived, hydraulic control is a valley wall constriction located downstream of the 1N01 Bridge on the mainstem of the Clavey River (Figure 1). A sharp constriction of opposing bedrock valley walls can create a backwater at very high flood flows, forcing a large point bar upstream or inducing a hydraulic jump that shapes a deep pool downstream.

Nested hydraulic controls that create nested depositional features are also exhibited on the Clavey River (Figure 2). Large-scale depositional features (e.g., boulder ribs, forced point bars comprised of boulders) are shaped by primary and secondary hydraulic controls during infrequent floods. Smaller-scale depositional features (e.g., gravel and cobble deposits in the lee of boulders) are associated with small secondary and tertiary hydraulic controls, and are scoured and reshaped by frequent small floods.

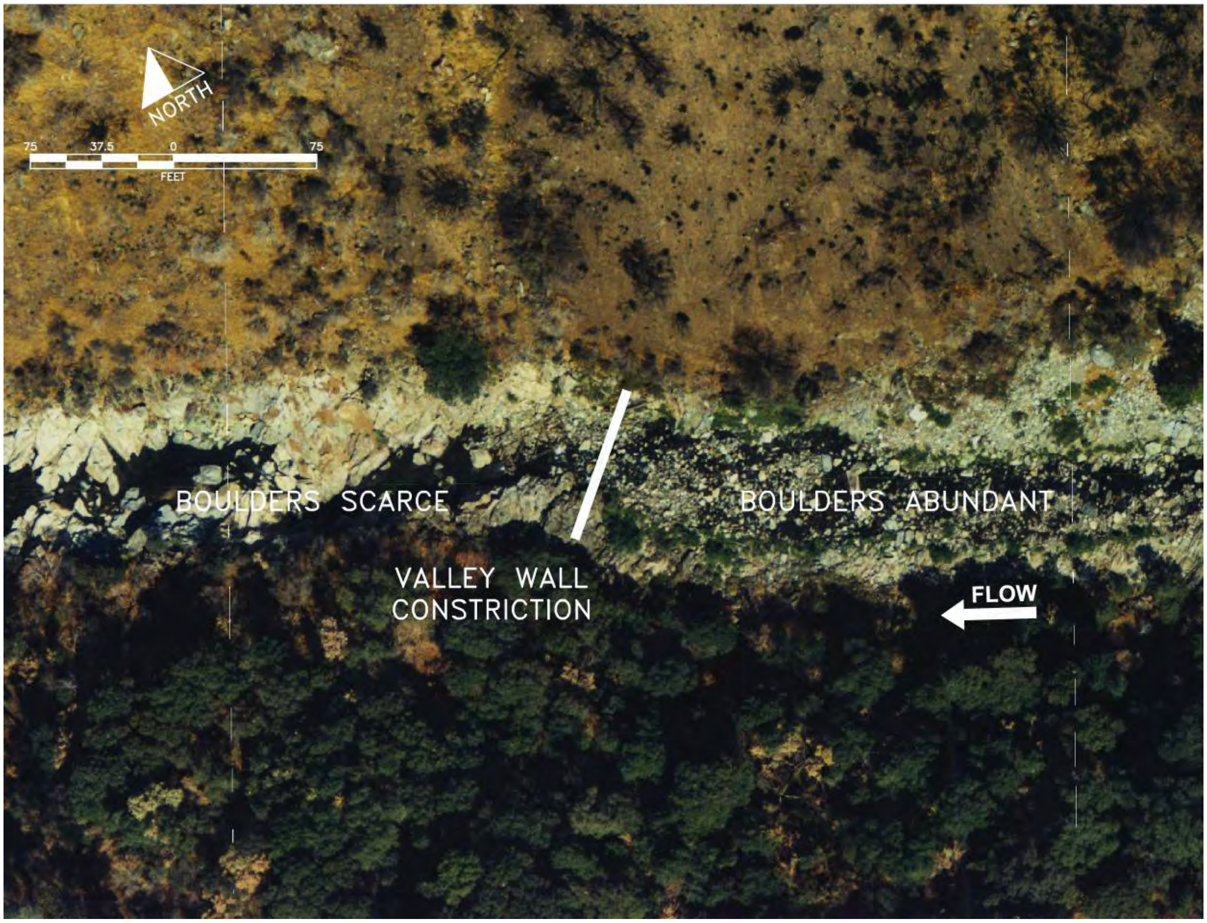


Figure 1. Example of a valley wall constriction functioning as a primary hydraulic control; note abundant boulders upstream of the constriction but their absence downstream. This photo was taken downstream of the Clavey River's 1N01 bridge, August 1988.

Attribute 2. Boulder-bedrock river ecosystems require flows that are annually variable. Annual hydrographs can be characterized by their variations in flow magnitude, duration, frequency, and timing, and they can be categorized into water year types. Further, annual hydrographs can be partitioned into discrete hydrograph components, including winter storm events, winter and summer baseflows, spring snowmelt peaks, and spring-summer snowmelt recession limbs. Each annual hydrograph component is important because it: (1) contributes to geomorphic processes that shape and maintain depositional and erosional features, (2) sustains varied life history and habitat requirements for those plant and animal species native to bedrock Sierra Nevada river ecosystems, and (3) perpetuates early-successional woody riparian communities (McBain and Trush 2004). An example of an annual hydrograph and its components has been drafted for the Clavey River at Buck Meadows, for water year (WY) 1979 (Figure 3).

Attribute 3. Episodic sediment delivery enhances spatial complexity. Hillslope mass wasting (such as from rock falls and bedrock shearing from canyon walls) episodically delivers colluvium (loose sediment). This colluvium is large enough to either create large depositional features in the channel, or to function as large-scale hydraulic controls capable of generating other prominent depositional features. Episodic events can impose hydraulic controls anywhere along the channel, and highly confined bedrock channels have tremendous

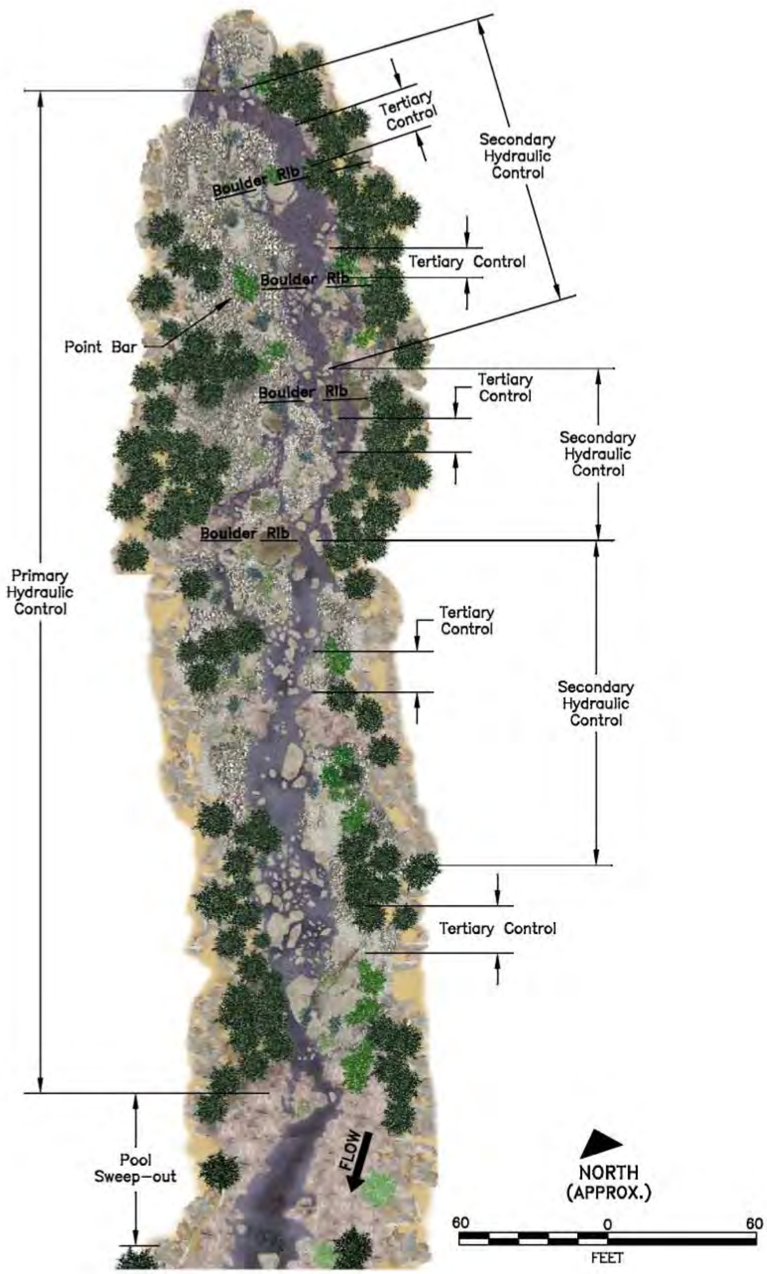


Figure 2. Stylized aerial photograph of nested hydraulic controls showing diversity of depositional features within one channel reach of the Clavey River.

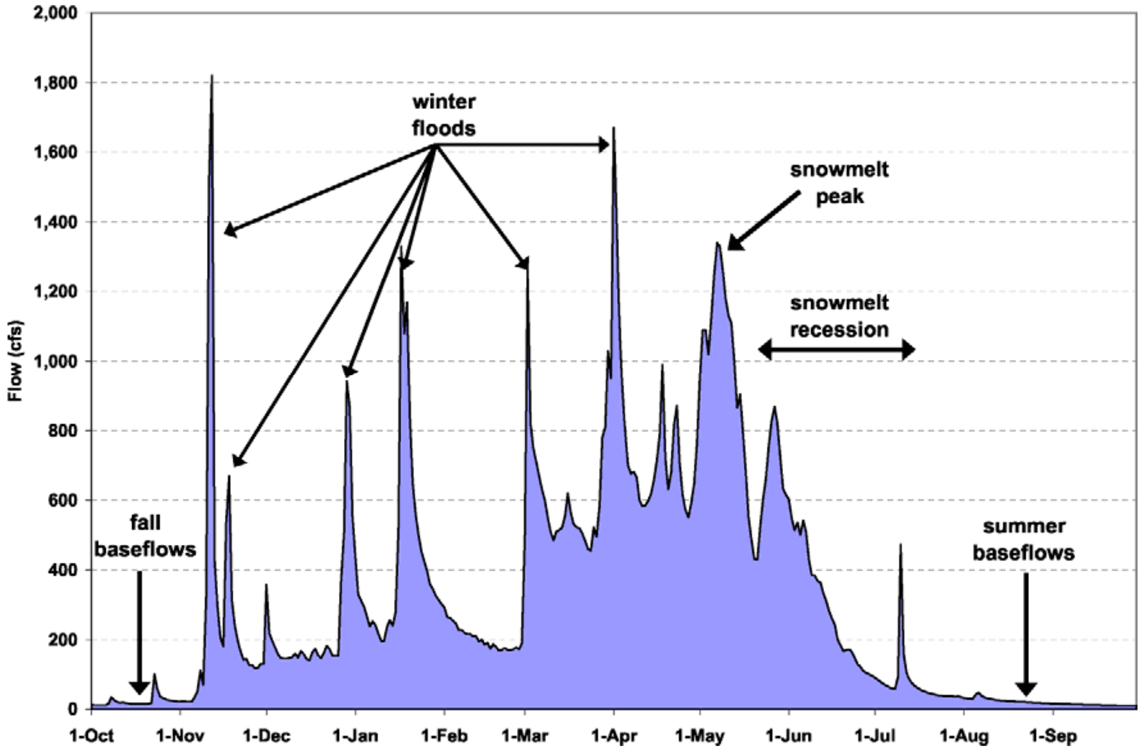


Figure 3. Annual hydrograph components in WY1979 from USGS Gaging Station No. 11283500, Clavey River at Buck Meadows.

power and transport capacity to move debris slides that are blocking or constraining the mainstem channel. Such an event is evident in the lower mainstem Clavey River. Geologically, the slide remains for a short time, but biologically, the slide's habitat remains for an extended period. Therefore, these episodic events supply a unique depositional environment and enhance spatial complexity.

Attribute 4. In boulder-bedrock rivers, channel maintenance requires a full range of flows. Flows of varying magnitudes and return periods must occur to initiate and maintain diverse erosional and depositional features of bedrock channels. The return periods below are provided as estimates; the actual return periods will vary with each river and climate regime. Some relationships between flood frequency and erosional and/or depositional processes include the following:

- **Flow frequencies of approximately 25-year (yr) annual maximum and greater.** These are infrequent, large, re-setting floods that: (1) significantly scour and redeposit large depositional features such as entire lateral bars, (2) reposition and aggregate large boulders into depositional features such as transverse boulder ribs, (3) periodically remove mature woody vegetation from bars and along channel margins, (4) encourage avulsions (soil movements) in broader channel reaches, (5) prevent steepening of riffles due to excessive boulder accumulation, and (6) remove boulders accumulating in bedrock pools.
- **Flow frequencies from 10-yr to 20-yr annual maximum floods.** These more frequent, lower magnitude floods: (1) significantly mobilize surface layers of large

coarse-grained bars that assist in minimizing woody riparian encroachment, (2) deposit smaller coarse depositional features associated with transverse boulder ribs and/or individual large boulders and bedrock outcrops, and (3) deposit silt and sand on floodplains and low terraces.

- **Flow frequencies up to 5-yr annual maximum floods with relatively small peak discharges.** These frequent snowmelt floods: (1) maintain a high turnover of finer-grained depositional features that are often associated with secondary hydraulic controls such as bars and transverse boulder ribs, (2) maintain high turnover of gravel deposits in bedrock pool tails, and (3) build limited floodplains.

Attribute 5. Maintenance of depositional features does not depend on the river's transport capacity of coarse bedload, but on nested hydraulic controls in a variable flow regime. Boulder-bedrock rivers have relatively large but generally unmet transport capacities for coarse sediment; simultaneously, bedrock rivers have generally low temporary storage capacities of coarse and fine sediment. In-channel storage capacity is greatly controlled by the nested hydraulic controls in a variable flow regime. The actual coarse sediment particles transported may move significantly, yet the total sediment volume stored in a channel segment remains unaffected. As expressed as nested hydraulic controls in a variable flow regime, complex hydraulics and channel morphologies establish the storage capacity for coarse sediment. Thus, the annual coarse sediment supplied to a channel segment may move significantly, but the annual coarse sediment volume stored may not change significantly.

Attribute 6. *Biological hotspots* occur at highly depositional channel reaches. *Biological hotspots* are defined here as short channel segments that support unique and/or diverse aquatic and riparian communities; they typically occur in reaches that are highly depositional, for example, where geologic features or major episodic events exert large-scale hydraulic control over deposition. These atypical and unique channel reaches exhibit prominent depositional features and even alluvial tendencies such as limited floodplains. These biological hotspots are highly dependent on snowmelt floods and recession flows.

Attribute 7. In prominent depositional features, water available as surface flow fluctuates seasonally and annually. The magnitude, duration, and timing of the annual snowmelt pulse flow can greatly influence water availability in prominent depositional features. As represented by variable hydrograph components, particularly the snowmelt recession limb and baseflow components, flow variation sustains surface flow pathways throughout the river corridor.

1.2. Project Objectives

The PIER Program supported this project to help develop a strategy for defining released instream flows that are:

- "Environmentally safe" (California Energy Commission 2003),
- Affordable, and
- Capable of generating a reliable energy supply.

A simplistic approach would be to consider a "release-and-see" strategy, in which higher and more variable streamflows would be released and then monitored over many years, to determine if more species of concern (say, rainbow trout) were produced. This simplistic approach would likely fail because any relationship between flows and fish might be correlated, but likely not causal. Therefore, the overall project objective was to outline a methodology that could be used to formulate example pulse flow guidelines, by quantifying relationships between channel morphology and processes, the snowmelt hydrograph, the biota, and water temperature.

The Clavey River is used as an example of an unregulated boulder-bedrock Sierra Nevada river ecosystem. Because this project was a *pilot study*, data collected were not as robust nor as extensive as would be required in a full-scale study; further, because only one river is used as an example, this study's results may not be applicable to all other Sierra Nevada rivers. However, although the data collected are preliminary, they are sufficient to support this methodology. The project's results should be interpreted as indications that this methodology can be useful, but the project's specific results should not be applied as finalized pulse flow guidelines.

The project study design addresses the following four project objectives, which were redrafted from the original contract objectives for greater specificity:

> **Objective 1:** Quantify mobilization thresholds for depositional features and establish trends in species habitat availability. For a boulder-bedrock channel reach of the mainstem Clavey River, quantifying mobilization thresholds and establishing trends are dependent on the magnitude, duration, frequency, and timing of: (1) the annual snowmelt flow regime, and (2) winter peak floods,.
>
> **Objective 2:** As represented by the annual snowmelt flow's rising limb, peak, and recession limb, assess how altering flows could directly and indirectly affect habitat used by Species of Concern (Section 1.2.1). Effects would be assessed by linking variable annual snowmelt flows to physical depositional/scour processes, depositional/scour morphological features, water temperature, and life history timelines.
>
> **Objective 3:** Demonstrate that: (1) if one designs variable winter and snowmelt pulse releases to re-create and maintain specific geomorphic and ecological thresholds, then many aspects of a regulated Sierra Nevada boulder-bedrock river ecosystem can be improved, and (2) if one impounds flow such that annual snowmelt flows

and winter peak floods are altered or eliminated, then geomorphic and ecological responses of a Sierra Nevada boulder-bedrock river ecosystem can be forecasted.

Objective 4: Given the results of the demonstrations in Objective 3, formulate example pulse flow guidelines, then highlight and evaluate uncertainties in the project's outcomes, recommend changes in field data collection and analytical procedures, recommend future sampling and analyses, and identify further information needed to quantify nested geomorphic thresholds, species habitat, and life history requirements that are relevant to winter floods and annual snowmelt flows.

1.2.1. Species of Concern

In river ecosystems, native species are numerous and only selected species can be evaluated. Numerous approaches have been developed for selecting certain species, such as targeting umbrella species, keystone species, flagship species, indicator species, and focal species (e.g., Lambeck 1997; Paine 1969). For this project, species and their sensitive life history stages were selected based on typical resource agency objectives, at-risk status, and potential as indicators of ecosystem function and integrity. The following species and their life history stages were selected for analysis:

- Willows of various species, at all life stages.
- Rainbow trout (*Oncorhynchus mykiss*) spawning and fry rearing.
- Foothill yellow-legged frog (*Rana boylii*), at early-life stages.
- Western toad (*Bufo boreas*), at early-life stages.
- Pacific treefrog (*Pseudacris* [*Hyla*] *regilla*), at early-life stages.
- Benthic macroinvertebrates (many species), at all life stages.

Sacramento sucker (*Catostomus occidentalis*) and California roach (*Lavinia symmetricus*) fry life stages were also evaluated, although not as intensively as the other species because suitable physical fry habitat requirements for both fish overlapped significantly with those of emergent fry habitat of rainbow trout.

The Clavey River was the first river in California to be designated a Wild Trout Stream. Under the California Department of Fish and Game (CDFG) Wild Trout Stream Program, designated streams are managed to preserve sustainable wild trout fisheries without hatchery supplementation (CDFG 1988). Trout populations throughout the Sierra Nevada have been altered by releases of hatchery strains of non-native origin. Although hatchery-reared trout have been released in the Clavey River, releases have been limited compared to other Sierra Nevada systems. Recent genetic studies suggest that the Clavey River rainbow trout population is likely an endemic population originating from redband and coastal trout (Clavey River Wild and Scenic River Value Review 1997). The California Department of Fish and Game and USFS include rainbow trout as a key management species in their agency plans (CDFG 1988; Clavey River Wild and Scenic River Value Review 1997).

Amphibians have significantly declined throughout the Sierra Nevada. Seven of nine frogs and toads are considered at risk of extinction (Centers for Water and Wildland Resources 1996). Most at risk are those that rely on river and riparian habitats: true frogs (*Rana* spp.) and toads (*Bufo* spp.) (Centers for Water and Wildland Resources 1996). Three amphibian species were selected to represent a range of habitat needs and life history strategies. The foothill yellow-legged frog is one of the most riverine-dependent ranid (true frog) species. This species has suffered serious declines and population fragmentation throughout its range and is currently listed as a Species of Special Concern. Western toads can use rivers for breeding but also breed in ponds, lakes, and wetlands. This species can breed in quiet waters along the river margins, in pools adjacent to the river, or in waters isolated from the river. Pacific treefrogs do not breed in flowing water. This species can breed in still pools associated within the mainstem channel or puddles and other waters isolated from the river.

1.3. Report Organization

This report follows the PIER Program's guidelines. The Introduction includes background information and project objectives. Section 2, Methods, provides descriptions of the study sites, field methods, data handling and modeling techniques, and the steps taken to synthesize all the information into example pulse flow guidelines. Section 3, Results, is presented in four main subsections: hydrologic analyses, geomorphic mobilization thresholds analyses, ecological analyses, and the synthesis. The products of the synthesis are found in subsection 3.6, Synthesis Implications, and 3.7, Example Pulse Flow Guidelines. Conclusions supporting the achievement of project objectives are found in Section 4, including the project's benefits to California.

In an effort to focus on important analyses, much information has been supplied in five appendices:

Appendix A. Attributes of Steep Boulder-Bedrock Sierra River Ecosystems

Appendix B. Depositional Feature Classification

Appendix C. Hydrologic Analyses

Appendix D. Modeled Bed Mobilization Thresholds

Appendix E. Riparian Vegetation Modeling Results

2.0 Methods

Project activities fell into three categories: (1) field data collection, (2) modeling and analysis, and (3) synthesis for formulating example pulse flow guidelines. Field data collection included the following:

- Classifying depositional features.
- Measuring physical variables, including discharge and stage height and water temperature.
- Establishing streamflow–stage relationships at key cross sections.
- Surveying water surface slopes.
- Painting, setting, and recovering tracer rocks.
- Mapping species habitats and documenting riparian tree seed releases.

Subsequent modeling and analyses included the following:

- Obtaining and assembling photographs, flow, temperature, and species-specific data available from several sources.
- Establishing streamflow mobilization thresholds for depositional features through observation and empirical hydraulic models.

Synthesis for formulating example pulse flow guidelines included the following:

- Establishing woody riparian vegetation relationships to channel morphology and the snowmelt hydrograph, in part using a recruitment box model.
- Generating habitat rating curves (discharge in cubic feet per seond (cfs) versus available habitat area in square feet [ft^2]).
- Combining the habitat rating curves with snowmelt hydrographs, water temperatures, species temperature thresholds, and species life stage periods to generate habigraphs (daily habitat abundance in ft^2 versus day of the runoff year).
- Overlaying particle movement and stage height data to further define habitat area as a function of flow magnitude and timing.
- Generating reference condition curves and defining some percentage of the reference condition at which ranges of flow magnitudes and timing are assured.

2.1. Study Site Location and Channel Reach Descriptions on the Clavey River

The Clavey River drains a 157 square mile (mi^2) watershed on the western slope of the Sierra Nevada Range and is a fifth-order tributary to the Tuolumne River (Figure 4). The watershed lies entirely within Stanislaus National Forest and 92% is in public ownership. Elevation in the watershed ranges from 9200 ft at the river's headwaters to 1200 ft at the Tuolumne River confluence (river mile [RM] 0.0). Precipitation varies with elevation. Above 5000 ft, precipitation is primarily snow; between 2800 and 5000 ft, precipitation is a combination of rain and snow. Snowfall below 2800 ft is unusual.

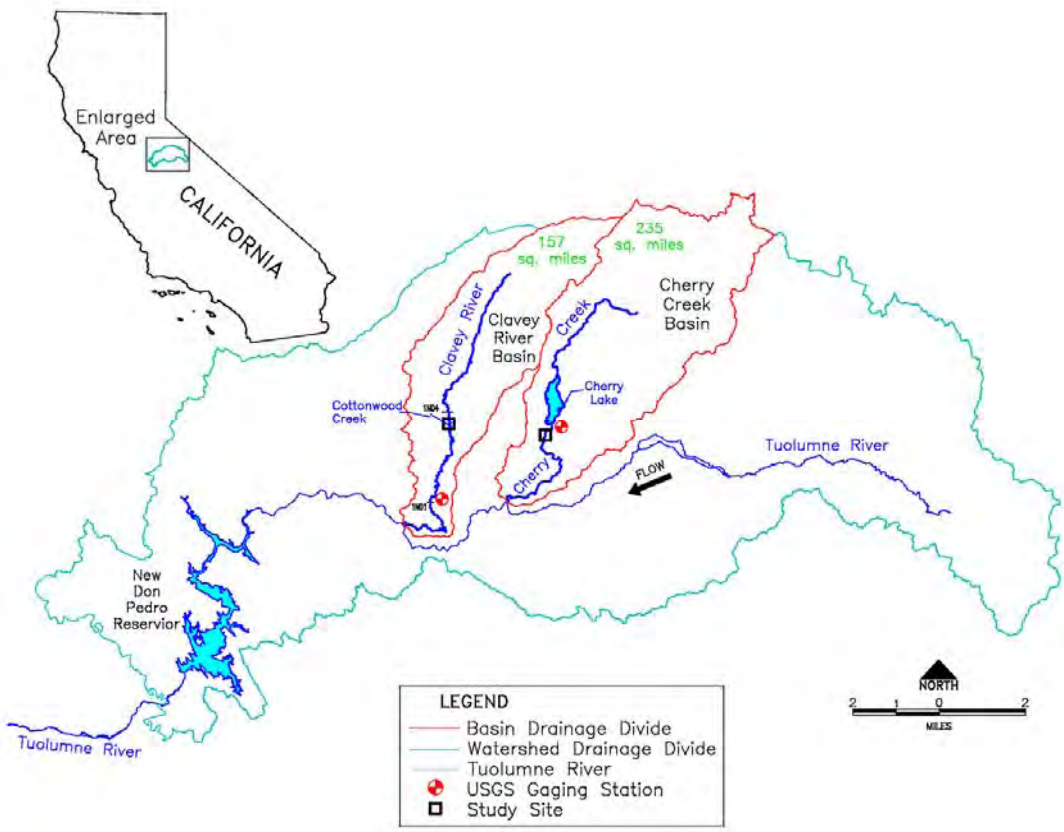


Figure 4. Clavey River and Cherry Creek vicinity map and study site locations.

The mainstem Clavey River begins at the confluence of Bell and Lily creeks and continues 32 miles downstream to its confluence with the Tuolumne River. Major tributaries (from headwaters to mouth) include: Rock Creek, Trout Creek, Two-mile Creek, Hull Creek, Cottonwood Creek, and Reed Creek. The mainstem river has been divided into four reaches based on landscape characteristics (Table 1) (Tuolumne County and TID 1990).

The project's mainstem study site is located in the Middle Reach and begins just downstream of Cottonwood Bar, at RM 16.5 and extends upstream to RM 17.0 (Figure 5).

The upstream and downstream boundaries of the study site are primary hydraulic controls created by extreme narrowing of the bedrock canyon walls. The study site was divided into four sub-reaches (Table 2). Cottonwood Creek flows into the Clavey River at RM 16.7, which is approximately midway in the project study site. River elevations in the project study site range from 3250 to 3400 ft. As estimated from 1:24,000 United States Geological Survey (USGS) topographic maps, the average mainstem channel gradient is 0.044.

Table 1. Clavey River mainstem reaches and general landscape descriptions.

Reach	Location	Average River Slope	Substrate	Landscape Description
Headwaters	3N03 Bridge to confluence of Bell and Lily creeks [RM 25.3 to RM 32.0]	0.032	Gravel/bedrock	Shallow canyon dominated by dense conifer forest
Upper	3N03 Bridge to Two-mile Creek [RM 20.0 to RM 25.3]	0.041	Boulder	Broad canyon with scattered forest openings and meadows
Middle	Two-mile Creek to Reed Creek [RM 15.0 to RM 20.0]	0.038	Boulder/bedrock	Steep, narrow canyon dominated by oaks and Ponderosa pine
Lower	Reed Creek to Tuolumne River [RM 15.0 to RM 0.0]	0.024	Bedrock/boulder	Deeply incised, sparsely vegetated canyon

Source: Tuolumne County and TID 1990

From the upstream boundary (Figure 6A) down to the Cottonwood Creek confluence, the mainstem channel is organized as a series of large boulder ribs with an average gradient of 0.048 (Figure 6B). Many diverse depositional features are hydraulically associated with these boulder ribs and strongly influenced by boulder size and boulder rib spacing. From the Cottonwood Creek confluence to the top of Cottonwood Bar, the mainstem channel also is a series of boulder ribs, but composed of smaller boulders and spaced wider apart (Figure 6C). A debris flow delta originating from Cottonwood Creek marks this sub-reach's upstream boundary. Perched flood deposits sporadically lining the left bank are likely a result of the sub-reach's gentler gradient, slightly wider channel width, and lower valley wall confinement. The Cottonwood Bar sub-reach (Figure 6D) is a low gradient (0.03), 290-foot-long right bank (RB, looking downstream) forced point bar in a wide channel bend, located immediately upstream of a primary bedrock hydraulic control. An actively scoured point bar, a narrow floodplain, an active side channel, and an aggraded floodplain, are all depositional features of Cottonwood Bar. From the downstream end of Cottonwood Bar to the downstream boundary of the project study site, bedrock outcrops anchor several boulder ribs. Mainstem channel width sharply decreases downstream as the bedrock valley walls constrict to form a waterfall at the entrance to a deep bedrock pool, called the Bob Pool (Figure 6E).

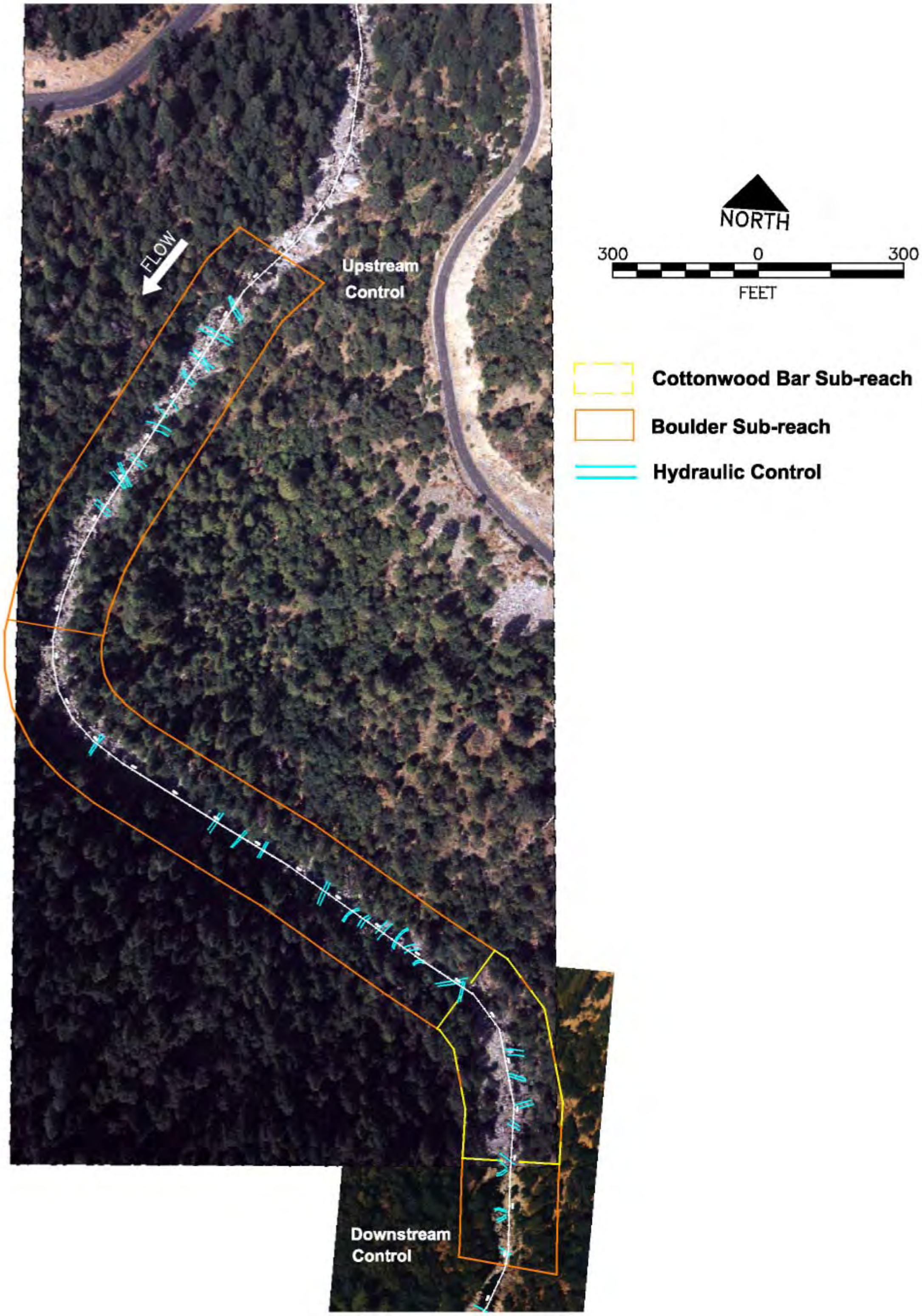


Figure 5. Clavey River study site.

Table 2. Clavey River sub-reach boundary locations by station, sub-reach lengths, and brief descriptions

Sub-reach in up- to downstream direction [survey station location]	Length (ft)	Description
Upstream boundary downstream to Cottonwood Creek [STA 29+60[a] to STA 38+70]	910	Tapering channel beginning wide upstream in steep reach, with large boulder ribs spaced closely to produce several deep pools
Cottonwood Creek downstream to Cottonwood Bar [STA 17+75 to STA 29+60]	1,185	Relatively narrow width with widely spaced small boulder ribs keyed into exposed bedrock
Cottonwood Bar [STA 13+90 to STA 17+75]	385	Forced point bar with floodplain and terraces
End of Cottonwood Bar to downstream boundary [STA 11+75 to STA 13+90]	215	Cascade of large boulders funneling downstream to the bedrock entrance (waterfall) of Bob Pool

[a] Cross sections were identified using standard surveying notation. "STA 29+60" indicates a cross section 2960 feet from river mile 0, which is at the confluence point of the tributary and the mainstem.

Figure 6A. At the top of the Clavey River study site looking downstream from the valley wall constriction.

Figure 6B. Large boulder ribs in the sub-reach above Cottonwood Creek confluence (cross section XS32+62) looking downstream, July 28, 2005; note flood scars on right bank alder.

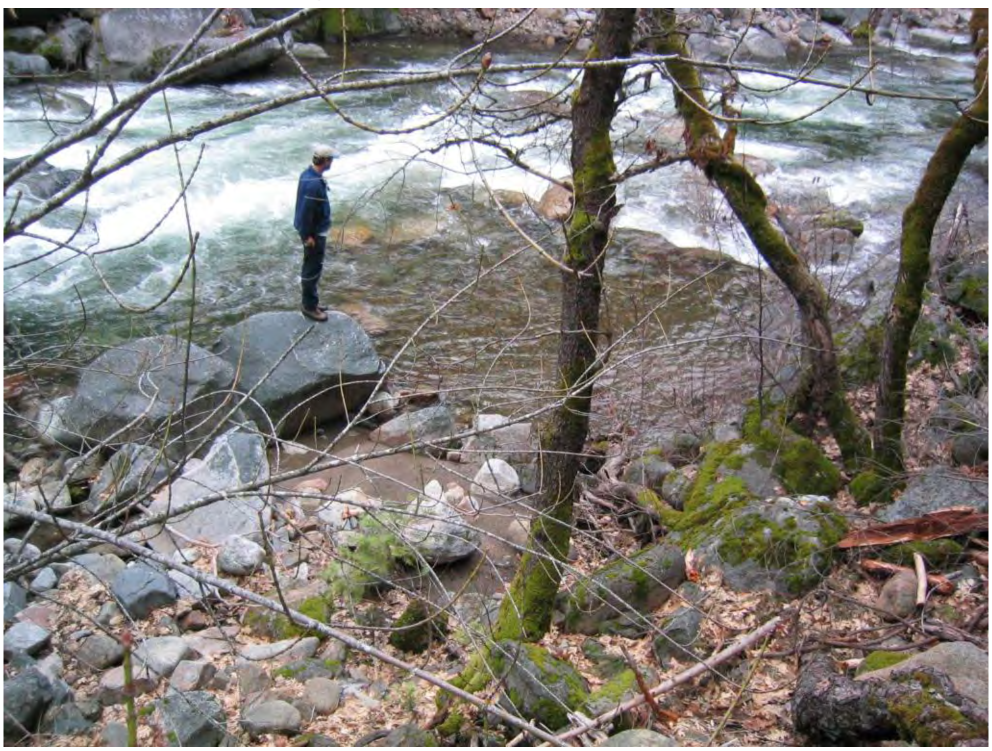


Figure 6C. Below Cottonwood Creek confluence looking downstream, March 5, 2005.

Figure 6D. Cottonwood Bar sub-reach looking downstream, July 8, 2005.

Figure 6E. Downstream end of Clavey River study site at bedrock entrance to Bob Pool, May 24, 2005.

2.2. Study Site Location and Channel Reach Descriptions on Cherry Creek

Cherry Creek, also a tributary to the Tuolumne River, drains a 235 mi^2 watershed adjacent to and east of the Clavey River watershed (Figure 4). Cherry Creek is regulated by Cherry Valley Dam (located at RM 11.6), which was constructed in 1956 and is a component of San Francisco's Hetch-Hetchy power generation and water supply system. Cherry Valley Dam impounds Lake Lloyd (also called Cherry Lake) with a capacity of 268,800 acre-feet, or 101% of the pre-dam total annual yield (based on water years 1910 to 1955). Water is also transferred to Lake Lloyd from Lake Eleanor, a 27,100-acre-foot reservoir on Eleanor Creek (a tributary to Cherry Creek). Water stored in Lake Lloyd is diverted from Cherry Creek to Holm Powerhouse via a 5.6-mile-long tunnel and penstock. After passing through the powerhouse, flow is returned to Cherry Creek approximately 0.7 miles upstream of the Tuolumne River confluence. Holm Powerhouse is operated as a power peaking facility, concentrating generation during daylight hours when energy is most valuable.

The Cherry Creek study site extends from RM 10.7 (240 ft upstream of the USGS gage) to RM 10.1 (Figure 7). From 1:24,000 USGS quad sheets, the average channel gradient in the study site is 0.02. The upstream portion of the Cherry Creek study site (from STA 29+20[1] to STA 16+20) is a low-gradient, alternate bar channel (Figures 7 and 8A). At STA 16+20, Cherry Creek enters a steep, confined bedrock canyon that extends 900 ft downstream to STA 7+20 (Figure 8B). From the canyon's end to the study site's downstream boundary, channel gradient decreases and an alternate bar morphology returns. Cherry Bar, a large forced point bar, extends from STA 60 to STA 500 (Figure 8C) with a gradient of 0.003. Downstream of the Cherry Creek study site, the creek enters a steep, confined canyon at RM 9.3 that continues until RM 2. Channel gradient through the canyon is 0.047.

2.3. Field Methods

Field surveys were conducted at the Clavey River and Cherry Creek study sites from March through September 2005. Field survey dates, flow conditions, and data collected are summarized (Tables 3 and 4).

2.3.1. Collecting Flow and Temperature Data

On February 22, 2005, McBain and Trush established a streamflow monitoring station at a former USGS gage site, to measure the WY2005 snowmelt hydrograph and summer baseflows. The project's monitoring station included a Stevens brand model PS2100 pressure transducer and temperature sensor, crest-stage gages, and staff plates from the former USGS gage. Elevations of all monitoring equipment were surveyed and referenced to USGS benchmarks (USGS brass survey monuments still survived). The pressure transducer measuring water depth was connected to a datalogger that recorded depth readings at

[1] Cross sections were identified using standard surveying notation. "STA 29+20" indicates a cross section located 2920 feet from river mile 0, which is located at the confluence point between the tributary and the mainstem.

15-minute intervals. Recorded depths were entered into a database and converted to 2005 daily average streamflows (cfs) using the most recent USGS Buck Meadows rating curve (last updated WY1995). At each cross section, installed crest stages were read during each site visit to determine the peak water surface stage since the previous site visit. Evidence of earlier high water marks deposited along the banks (e.g., debris lines of rafted bark and conifer needles) were also surveyed to provide additional peak stage information. An additional gaging station at the 1N04 Bridge could not be installed due to high flow conditions by the time the project was funded and roads became passable.

Data were obtained from three USGS gages:

- USGS Gage No. 1283500, at the 1N01 Bridge, Clavey River near Buck Meadows.
- USGS Gage No. 11277000, at Cherry Creek near Hetch Hetchy.
- USGS Gage No. 11277300, at Cherry Creek below Valley Dam.

Limited water temperature data were available. During Spring and Summer 2005, thermographs deployed at several locations on Cottonwood Bar failed due to a software incompatibility. The only temperature data set for WY2005 was from the gaging station at the 1N01 Bridge, 7.6 river miles downstream from the 1N04 Bridge (Figure 4). The best source for temperature data was Turlock Irrigation District (TID), which monitored water temperature at several locations from WY1986 through WY1988 to calibrate a water temperature model. These data, however, are no longer archived at TID or with the consultants who prepared the model, and could not be obtained. TID's temperature model results were the best water temperature data prior to WY2005. The model was constructed using the U.S. Fish and Wildlife Service Stream Network Temperature (SNTEMP) Model (Theurer et al. 1984) and predicts seven-day average water temperatures at nodes spaced 3.1-mi apart. Model results were available for WY1967 through WY1976 (Tuolumne County and TID 1990). The USGS also took spot temperature measurements at the Buck Meadows gage when the gage was operated. These spot measurements were compared to model predictions for each year to verify predicted temperatures.

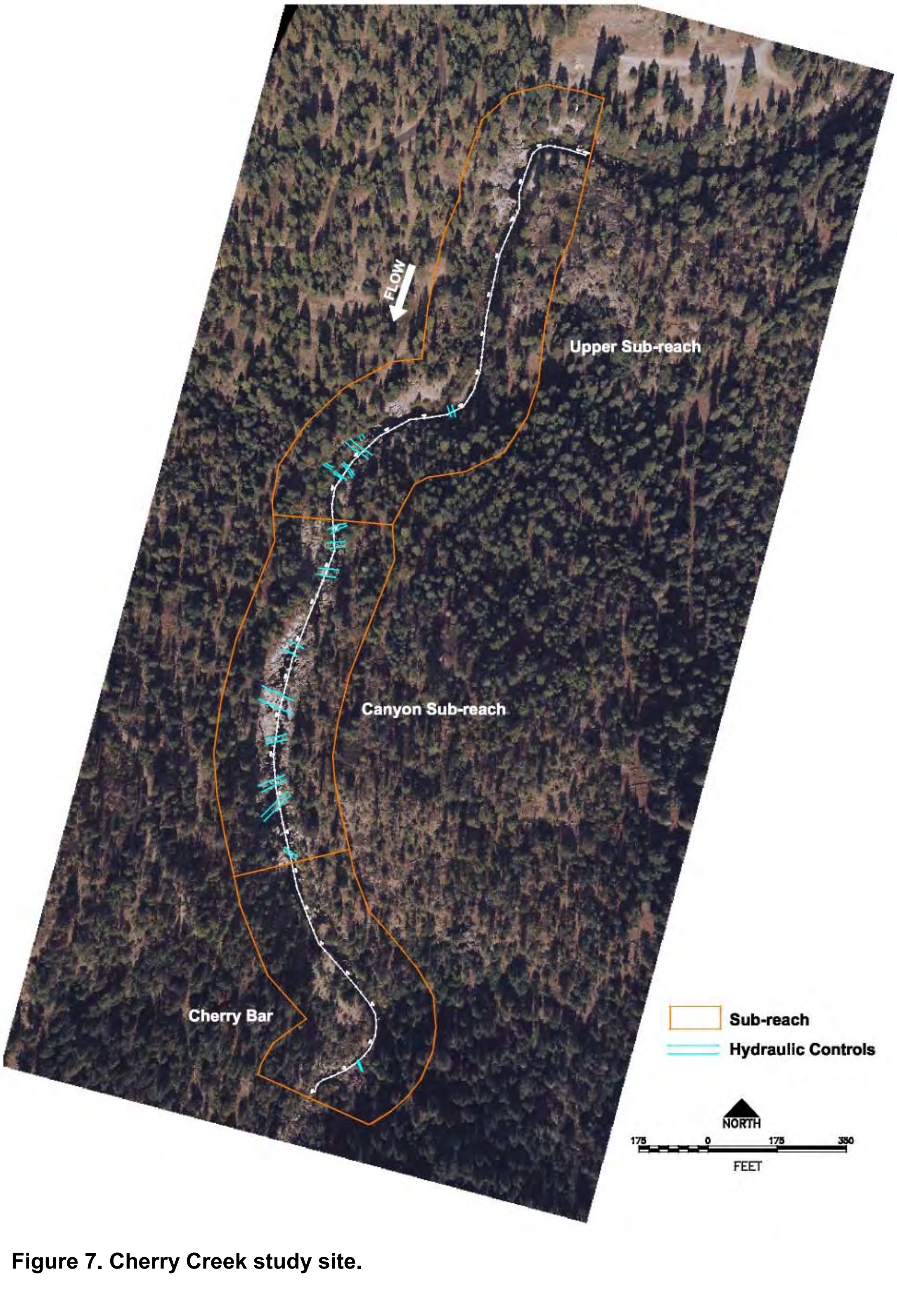


Figure 7. Cherry Creek study site.

Figure 8A. Top of the Cherry Creek upper sub-reach at the USGS Gage site looking upstream, May 24, 2005.

Figure 8B. Cherry Creek's canyon sub-reach looking downstream, July 27, 2005.

Figure 8C. Cherry Bar sub-reach looking downstream, May 24, 2005.

2.3.2. Classifying Depositional Features

A classification scheme for defining depositional features in steep boulder-bedrock rivers (Table 5) was a handy tool for systematically investigating geomorphic streamflow thresholds. Ten types of depositional features were observed in the Clavey River between the 1N01 Bridge and 1N04 Bridge (Figure 4) on the mainstem Clavey River, but these classifications would apply equally well to Cherry Creek. Example photographs and detailed descriptions of each type of depositional feature are found in Appendix B.

2.3.3. Documenting Channel Morphology

Mainstem channel surveys in the Clavey River study site documented: (1) channel cross section shape and slope, (2) location and texture of selected depositional features, (3) location and height of boulders acting as hydraulic controls for those deposits, (4) flow stages observed and marked in WY2005 including high water marks from the WY2005 and WY1997 floods, (5) bank position of established riparian vegetation, and (6) locations and elevations of caddisfly stone cases from WY2005. Upstream of Cottonwood Creek, three pairs of full-channel cross sections and one partial-channel cross section were established to represent the boulder sub-reach (Figure 9). Five cross sections were surveyed on Cottonwood Bar and short distances upstream and downstream (Figure 10).

Table 3. Summary of data collected at the Clavey River study site.

Date	Daily average flow at 1N01 (cfs)	Daily average flow scaled to 1N04 (cfs)	Habitat mapping	Photo points	Flow stage	Seed release	Cross section surveys	Pebble counts
May 24, 2005	1,798	1,099			●	●		
May 27, 2005	1,819	1,112	●	●	●			
June 8, 2005	665	406	●	●	●	●		
June 23, 2005	546	334			●	●		
July 8, 2005	301	184	●	●	●	●		
July 28, 2005	93[1]	57[1]	●	●	●	●		
August 29–September 3, 2005	46[2] [19][3]	28[2] [12][3]	●	●	●	●	●	●

[1] Flow estimated. Gage out of water July 20–29, 2005.
[2] Flow computed from gage rating curve.
[3] Flow from discharge measurement August 31, 2005.

All cross sections were surveyed with an autolevel using methods described by Harrelson et al. (1994). At each cross section, the following were recorded: (1) current flow stage, (2) flow stage markers placed during the WY2005 study period, (3) high water marks from the WY2005 and WY1997 floods, (4) locations and heights of boulders associated with lee and obstruction deposits, (5) locations and elevations of caddisfly stone cases, and (6) root elevations of established riparian vegetation. Each cross section was photographed with the survey tape in place to record location, flow conditions, and other features at each site. All cross sections were monumented with ½-inch rebar and located on photo basemaps. Pebble counts (Wolman 1954) quantified bed texture in selected depositional features.

In the Cherry Creek study site, cross sections were established at Cherry Bar and at two locations upstream (Figure 11). At Cherry Bar, four cross sections were established to document bar and channel morphology, flow stage, and established vegetation.

Table 4. Summary of data collected at the Cherry Creek study site.

Date	Daily average flow (cfs)[1]	Habitat mapping	Photo points	Flow Stage	Seed release	Cross section surveys	Pebble counts/marked rocks
March 22, 2005	17					●	●
May 25, 2005	2380		●	●			
May 26, 2005	1790	●					
June 9, 2005	563	●	●	●	●		
June 22, 2005	681 [734][2]	●	●	●	●		
July 9, 2005	360 [131][2]	●	●	●	●		
July 27, 2005	18	●	●	●			
August 31–September 4, 2005	15			●		●	●

[1] Provisional data USGS gage Cherry Creek below Valley Dam near Hetch Hetchy (No. 11277300)
[2] When flow changed significantly during the 24-hr period for which daily average flow is computed, mean flow was computed from 15-minute data for the hours during which mapping was conducted. The mean 15-minute flow during mapping surveys is shown in brackets.

Ground photographs were taken during each habitat survey to record flow conditions throughout both study sites. Photopoints were established on the Clavey River (n = 13) and Cherry Creek (n = 12) during the first habitat mapping survey in May 2005. A monument for each photopoint was located with a 2.5 inch-diameter metal washer affixed to a rock or boulder. For photopoints on bridges, locations were marked on the bridge railing. Each photopoint was reoccupied during each habitat survey using a Sony Powershot S230 3.2 megapixel digital camera. After the first survey, photopoints were plotted and laminated for field use. The laminated plots helped align photographs to keep viewpoints consistent between streamflows. After each field visit, all photographs were downloaded and logged into a spreadsheet for querying and retrieval. Photographs varied from 180° panoramas to single photographs of unique habitat features. Three time-lapse cameras were also installed at the study sites.

Table 5. Depositional features observed on the mainstem Clavey River, typical of steep, boulder-bedrock Sierra Nevada rivers.

Depositional Feature	Definition of Depositional Feature
Aggraded Floodplain	An almost flat or gently sloping surface (away from the thalweg) typically associated with a point bar and created by progressive overbank deposition of silt and sand.
Boulder Rib	Boulders arranged in a transverse line spanning the channel width.
Point Bar	A large scale bar usually half a channel meander wavelength long with a relatively short radius of curvature, where the thalweg is located toward the outside bank and coarse bedload is transported across its surface rather than along its thalweg.
Lateral Bar	Cobble and small boulder deposits sheltered from large floods by bedrock protruding from the valley wall or large boulders protruding from the riverbank.
Boulder Cluster	Collection of boulders, two or more, each in physical contact with one another.
Lee Deposit	Accumulation of fine/coarse sediment immediately downstream of a roughness element, commonly a single boulder or boulder rib, with the deposit's surface sloping negative, that is, towards the channel bed
Obstruction Deposit	Accumulation of fine/coarse sediment upstream of a roughness element, commonly with the deposit's surface sloping steeply positive, that is, towards the surface.
Perched Deposit	Accumulation of fine/coarse sediment in local depressions formed by coarser particles or bedrock that is elevated above the thalweg, commonly with the deposit's surface slope appearing flat or reflecting a high flow slope.
Pool/Run Tail Deposit	Fine/coarse sediment deposited at or near a pool or run's downstream control at baseflow stage, with the sediment deposit's surface generally sloping towards the water surface.
Eddy Deposit	Fine sediment deposited during late stages of the falling flood limb.

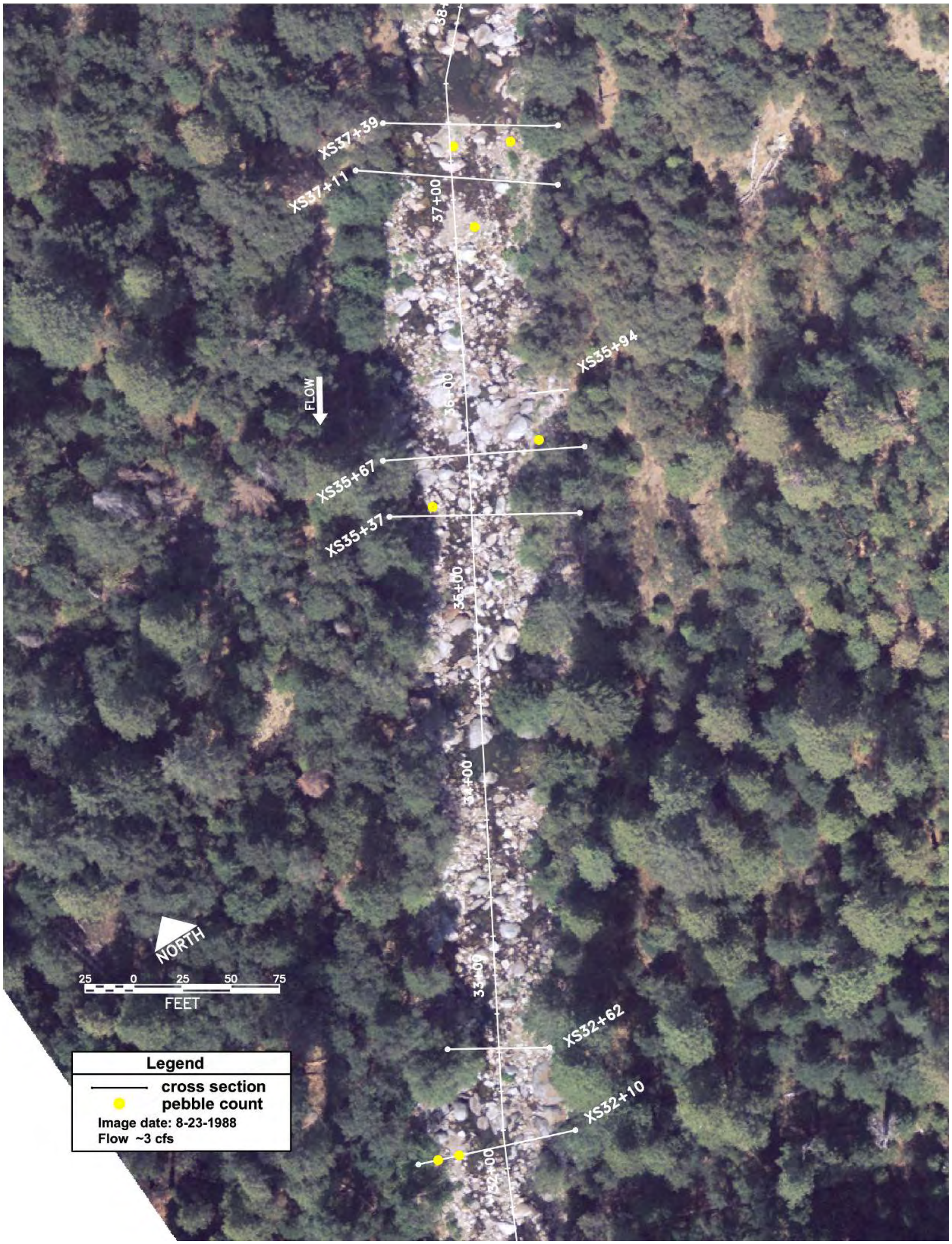


Figure 9. Locations of cross sections in the Clavey River's boulder sub-reach.

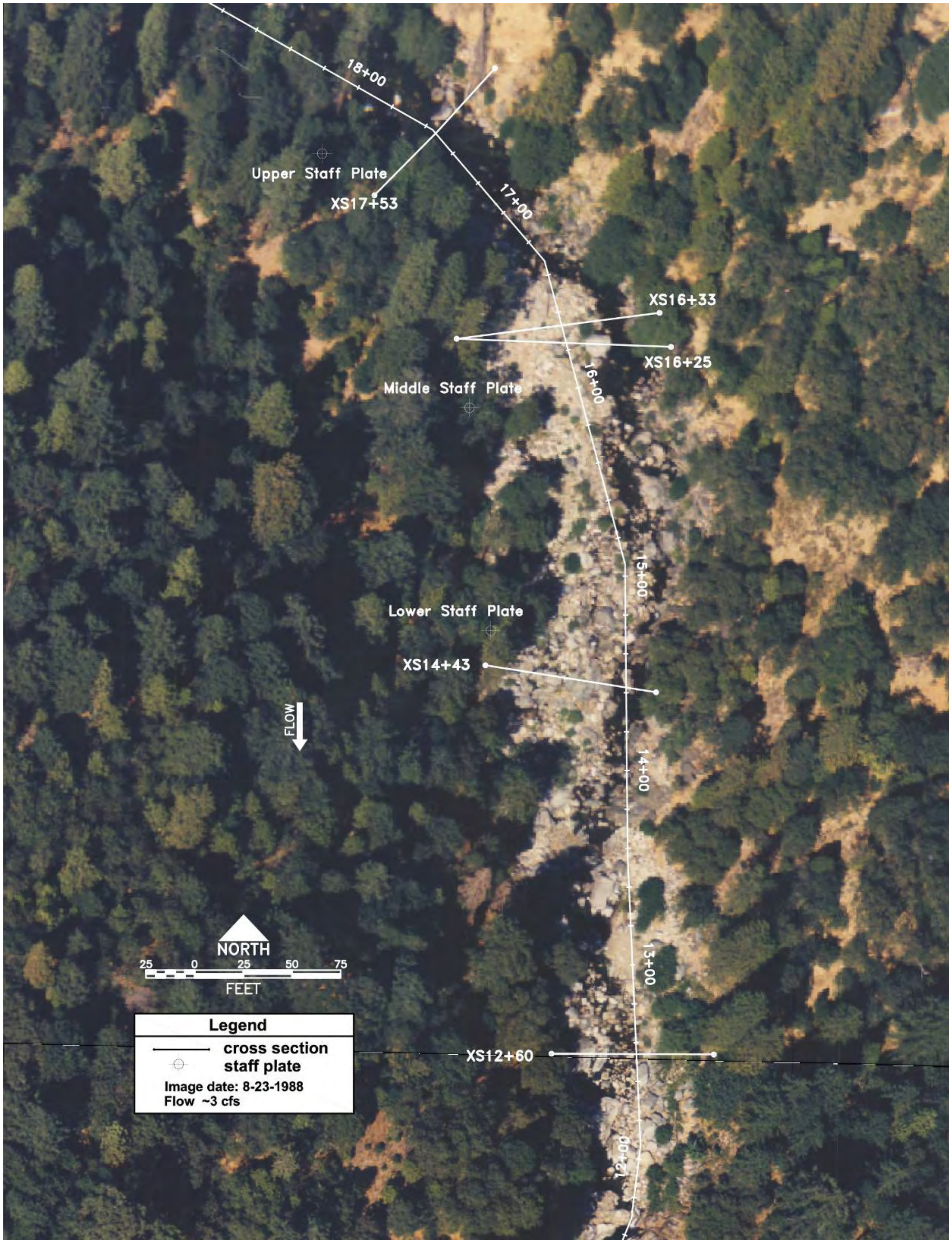


Figure 10. Locations of cross sections in the Clavey River's Cottonwood Bar sub-reach.

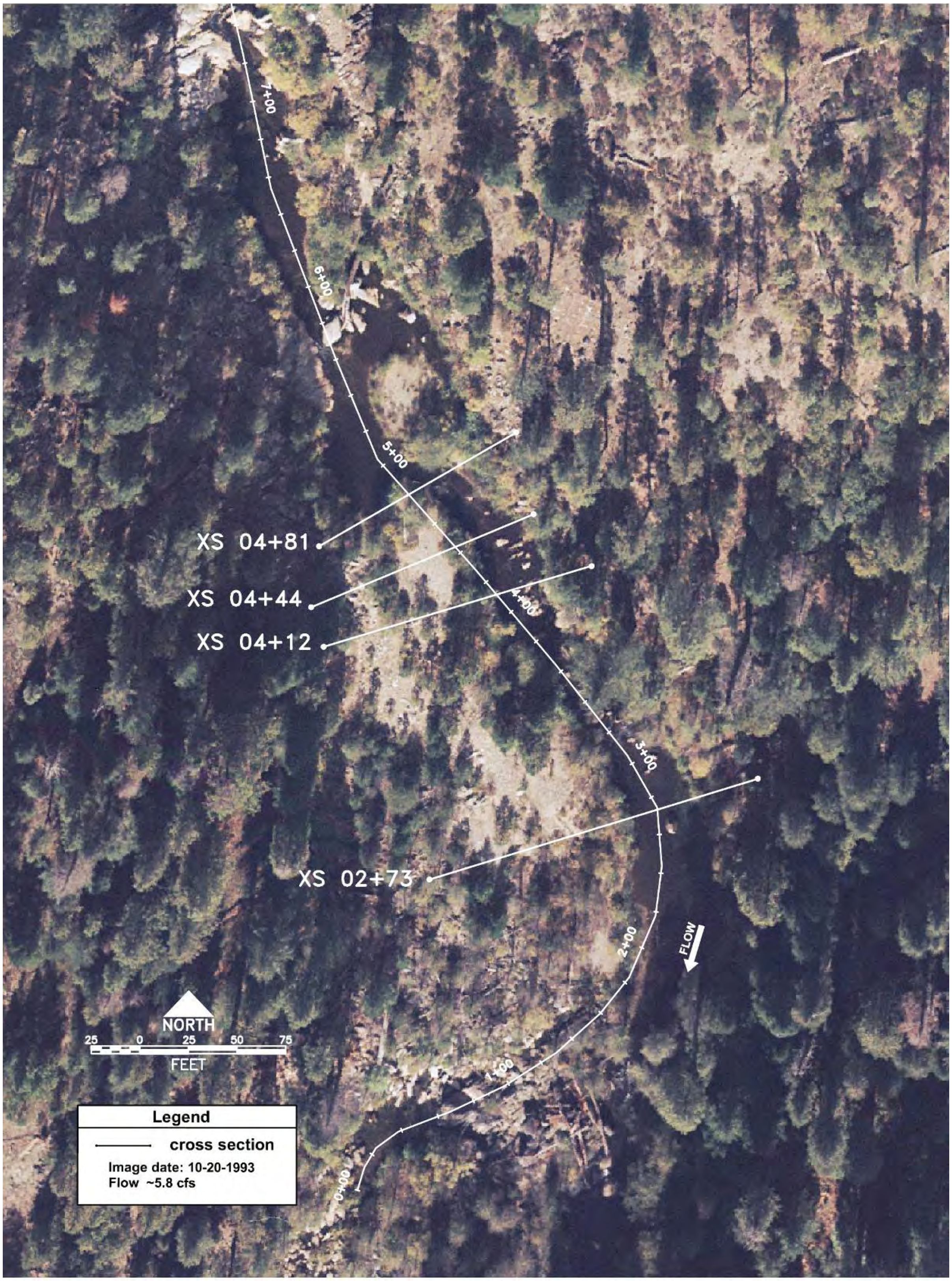


Figure 11. Locations of cross sections in the Cherry Creek study site.

2.3.4. Experimenting with Tracer Rocks

Tracer rock experiments were performed previously by others; these data were complemented with a limited tracer rock experiment on Cherry Creek in WY2005 and analysis of ground photographs that documented depositional features.

In 1992 and 1993, tracer rock experiments were performed at a site immediately downstream of the 1N01 Bridge ("Lower Bridge Bar"), approximately 7.5 miles downstream of the Cottonwood Bar study site (named "Upper Bridge Bar" in IRE 1994). Three sets of tracer rocks were painted in-situ in cobble/gravel deposits on the bar; one set was on XS 1035[2] and two sets were on XS 1120 (see IRE 1994 for cross section locations and descriptions). These tracer rocks were monitored for the WY1992 and WY1993 high flow years. Using the WY1993 data, bed mobility was modeled at the Upper Bridge Bar XS 1029 and the Lower Bridge Bar XS 1020 (IRE 1994). Flow predictions to mobilize the D_{85} and D_{50} for the cobbles at the head of each bar were made using the methods of Bathurst (1987) and Wiberg and Smith (1987).

On March 22, 2005, tracer rocks[3] were installed in two cross sections on a Cherry Bar cobble deposit. Pebble counts in March 2005 documented a D_{84} = 100 millimeters (mm), D_{50} = 62 mm, and D_{31} = 44 mm at XS 200; at XS 400, pebble counts documented a D_{84} = 89 mm, D_{50} = 52 mm, and D_{31} = 37 mm. Thirteen D_{50}, D_{84}, and D_{31} tracer rock sets were placed at XS 200, and fifteen tracer rock sets were placed at XS 400. Shortly thereafter, a peak flow of approximately 3390 cfs was released from Cherry Lake Dam. Tracer rock mobilization on both cross sections was documented after flows receded.

2.3.5. Compiling Ground Photographs

Field evidence, hydrologic records, and ground photographs were used to identify flow thresholds at which geomorphic features began to move. Ground photographs of individual depositional features before and after a peak flow event provide indisputable evidence for determining mobility thresholds. However, this method had limitations. First, only the largest peak flood occurring between the two photo dates could be associated with changes in bed surface composition. Second, the scales of many photos were too small to discern whether smaller particles moved. Third, the extent of mobilization was difficult to quantify (e.g., did 50% of the D_{50} and larger particles move, or 70%?).

During WY1997, an approximate 75-yr flood event occurred on the Clavey River. Ground photographs at various locations, taken at varying times, were compared to assess the flood's effects on scour/fill of depositional features, movement of individual boulders, and

[2] Cross sections were identified by standard surveying notation. " XS 1035" identifies a cross section 1035 feet from river mile 0, which is defined as the confluence point of the tributary and the mainstem river.

[3] Rock sizes were defined by the "D_{xx}" notation. For example, D_{50} = 60 mm indicates that of a certain set of rocks, 50% of the rocks were finer/smaller than 60 mm.

changes in woody riparian vegetation. Photographs from the following locations and years were examined:

- At Cottonwood Bar and in the boulder sub-reach, photographs from eight photo points taken during WY1993 and WY2000.
- At the 1N01 Bridge, photographs from WY1993, WY2002, and WY2005.
- At the 1N04 Bridge, paired photographs from WY2000 and WY2005. The WY2005 photographs were taken after the peak WY2005 runoff event occurred. This was the biggest flood between WY2000 and WY2005 (approximately a 4.4-yr flood).

2.3.6. Collecting Data to Support Willow Life History Model

Willow seed release varies annually and by species. An early task was to complete a woody riparian tree phenology for each willow species found at the mainstem Clavey River study site. Seed release periodicity required field visits to observe species-specific willow seed release periods; a literature search complemented the one-year field study.

White alder and bigleaf maple seeds remain viable for more than one year, and therefore did not require a detailed phenological field study. For both species, seed rafting by peak floods was documented by noting the elevation of rafted flood debris, which included seeds, on surveyed channel cross sections.

On the Clavey River, a single cross section (XS 16+33) was selected to represent Cottonwood Bar, and another cross section (XS 32+62) was selected to represent a small point bar between boulder ribs. A stage–discharge rating curve at XS 16+33 was developed from the stream gaging and field surveys.

2.3.7. Quantifying Habitat with Expert Habitat Mapping

The project adopted a field-based methodology called *expert habitat mapping* (EHM) (McBain and Trush 2003). The premise for using EHM on the Clavey River and Cherry Creek was simple: rather than model hydraulics to then model habitat availability, biologists quantified the area of good habitat by mapping it directly in the field during several WY2005 snowmelt recession streamflows. This approach avoided many pitfalls in traditional hydraulic and habitat models, but required extensive fieldwork.

Traditional models such as Physical Habitat Simulation (PHABSIM) (Bovee et al. 1998) or River 2D (Steffler and Blackburn 2002) are used to quantify the relationship between flow magnitude and available habitat. These models predict flow depth and velocity over a range of flows in a cross section or short channel reach; the flow depth and velocity conditions are then used to predict weighted useable habitat area, based on quantitative habitat suitability criteria. However, the models' predictions of depth and velocity are of limited accuracy at a scale necessary for assessing habitat, particularly in hydraulically complex channels such as the Clavey River mainstem. Also, models can be applied only to species for which habitat suitability indices have been developed. Habitat suitability indices have been developed for many commercial or recreational fish species but are not available for many ecologically sensitive or non-commercial species. Therefore, the Clavey River was deemed a good candidate for EHM instead of models such as PHABSIM of River 2D.

In EHM, an expert biologist identifies a patch of channelbed that is considered good habitat for a particular species and life stage, and draws the patch onto a basemap. Each identified habitat patch is called a *habitat polygon.* For species targeted in the project, habitat suitability was based on published descriptions of suitable habitat and professional experience. Prior to the first mapping event, the project team conducted a two-day reconnaissance survey and habitat mapping training at the study sites; the team was led by Don Ashton, U.S. Forest Service herpetologist (amphibian habitat) and Bill Trush of McBain and Trush, Inc. (fish and benthic macroinvertebrate habitat). During this training, project biologists developed mapping habitat guidelines to ensure consistent interpretation of mapping results. Good species habitat was mapped at Clavey River and Cherry Creek study sites, during the descending limb of the WY2005 snowmelt hydrograph. Mapping was conducted during five flows ranging from 1112 cfs to 12 cfs (USGS gaged streamflow estimates scaled to streamflows in the sub-reaches) between May 26 and September 3, 2005. For each mapping event, the habitat mapping team walked the study site and drew habitat polygons onto laminated basemaps (see Section 2.3.7). During the 1112 cfs and 406 cfs Clavey River mapping surveys, high flows prevented access into or across the channel, and habitat was mapped from the right bank for the entire reach. During low flows, the survey crew could access the entire channel, so mapping was conducted from both banks and from within the channel. Habitat polygons for all species and life stages were drawn onto the same photoset; different colors or mapping symbols were used to differentiate between species and life stage. Field notes were also recorded directly onto basemaps. During each survey, flow stage was recorded at three staff plates installed at Cottonwood Bar. Upstream of Cottonwood Bar, flow stage was recorded at ten locations.

Habitat mapping requires a good basemap that must: (1) be of appropriate scale for mapping (approximately 1 inch to 20 ft or less), yet be scaled properly to accurately and efficiently map habitats, and (2) depict substrate, boulders, large wood, and other prominent features to serve as visual reference points. Basemaps for habitat mapping were generated from available aerial photographs. For the Clavey River study site, basemaps were generated from color aerial photographs taken on August 23, 1988, at a scale of 1:6000. Printed enlargements of these photographs (where available) and photograph negatives were scanned at 2000 dots per inch (dpi) for processing. Each scanned photograph was geocorrected using a first-degree polynomial transformation in ERDAS geospatial satellite image processing software and 1:24,000-scale USGS Digital Orthophoto Quarter Quadrangles as the reference base. Geocorrected photographs were referenced to the California Stateplane Zone 3, NAD83 coordinate system. Final basemap layouts were generated in AutoCAD. For Cherry Creek, basemaps were generated from 1:6,000-scale color aerial photographs taken on October 20, 1993 and obtained from the U.S. Forest Service. Photograph negatives were scanned at 2000 dpi. Photographs were geocorrected using the same methods described for the Clavey River study site. All photographs for each study site were plotted at a scale of 1:240 (1 inch = 20 ft) and laminated for field use. Basemaps also included river stationing at 20-ft intervals to aid in orientation and mapping.

Accurately mapping the habitat polygons onto the basemaps was sometimes difficult. The 1988 photographs were 17 years old and taken before the WY1997 flood; vegetation, large snags, and some large boulders had changed. Also, for much of the Clavey's channel, from downstream of Cottonwood Creek (STA 28+20) to the upstream end of Cottonwood Bar (STA 17+00), shadows obscured features in some photographs. To reduce error in polygon location and maintain consistency in habitat interpretation and mapping locations between each streamflow surveyed, the following measures were taken:

- During the May 2005 survey, water surface markers were placed at 40-ft to 360-ft intervals along the channel. Marker locations were plotted onto the basemaps as tangible landmarks.
- Except for the May 2005 survey, the same staff ecologist interpreted and mapped habitat polygons for every mapping event.
- Where needed, distance along the channel was measured using a 200-ft tape and compared to stationing plotted on the basemaps to aid in orientation.
- Maps from the each survey were consulted during subsequent surveys so that all polygons mapped at one streamflow (i.e., the prior survey) could be relocated for mapping at the next lower streamflow (i.e., the subsequent survey).

After each round of field mapping, field habitat maps were photocopied and archived. Habitat polygons were digitized using AutoCAD software. No boundary adjusting, smoothing, or aggregating was performed. Draft habitat maps (polygons plotted onto aerial photograph backgrounds) were reviewed by the ecologist who conducted the mapping. Once a habitat map was finalized, each polygon was given a reference identification number associated with a species and life stage.

After habitat maps were generated, no validation of the maps (for example, by electrofishing, amphibian census, or macroinvertebrate density estimates) was performed. The primary purpose of this EHM and subsequent analyses was to establish the utility of this methodology for formulating example pulse flow guidelines. If an agency or utility desired to use this methodology to formulate actual pulse flow guidelines, validation of the mapping would be recommended. In addition, an analysis of the uncertainty and variation in all parameters would be recommended.

2.4. Data Analyses and Modeling Methods

Data analyses included estimating streamflows in WY2005, re-creating annual hydrographs dating back to the early 1960s, classifying water years and runoff years, partitioning annual hydrographs into separate hydrograph components, reconstructing flooding histories, and estimating flood frequencies.

2.4.1. Estimating Daily Average Streamflows for WY2005

To estimate daily average streamflows for the Clavey River study site, data from the nearest USGS gage were scaled by drainage area. The nearest gage is Gage No. 11283500 (Clavey River near Buck Meadows), which is located 7.6 river miles downstream of the Clavey River study site. The USGS operated the gaging station, which is 250 ft upstream of the 1N01 Bridge at RM 8.8, from 1959 to 1995; Gage No. 11283500 is also called the "1N01 gaging station." No other flow data were found, except for one instantaneous peak flow estimate occurring in WY1997. By multiplying the 1N01 gage data by a ratio of drainage areas of the Clavey River study site and the 1N01 gaging station, flows for the Clavey River study site were estimated (Table 6); the ratio is 0.61.

Table 6. Drainage areas for the Clavey River study site and the 1N01 gaging station.

Location name	Location in RM	Drainage area (mi^2)
USGS Gage No. 11283500 (the "1N01 gaging station")	RM 8.8	144
Clavey River study reach	RM 16.4	88

However, due to shifts in the rating curve, all 2005 daily average streamflows for the Clavey River study site should be considered approximate.

2.4.2. Constructing Clavey River and Cherry Creek Annual Hydrographs

Annual hydrographs (flow versus time) were constructed for the Clavey River and Cherry Creek. For the Clavey River, the USGS's 1N01 gaging station (Gage No. 11283500) provided daily average streamflows from WY1960 to WY1983 and from WY1987 to WY1994. To fill the gaps in the USGS hydrologic record, daily average streamflows were modeled by the Turlock Irrigation District, from WY1984 to WY1986 and from WY1996 to WY1999. There are no daily streamflow estimates, and therefore no measured annual hydrographs, from WY2000 to WY2004, but this record sufficiently represents a wide range of water year types.

Annual hydrographs for Cherry Creek were constructed to represent regulated and unregulated conditions. Unregulated Cherry Creek flows are represented by data from USGS Gage No. 11277000, which provided daily streamflows and flood peaks from WY1915 through WY1955. Following dam construction in 1956, the USGS moved and renamed the gaging station to Cherry Creek below Valley Dam, USGS Gage No. 11277300. The regulated data are available from WY1957 until the present. Drainage area decreased when the gage was moved, from 118 mi^2 to 111 mi^2.

Annual hydrographs were generated over time periods representing the water year (October 1 to September 30). Annual snowmelt hydrographs focused attention to periods of snowmelt, from April 1 to August 31.

2.4.3. Classifying Water Year (WY) and Runoff Year (RY)

Water years were classified into five types, ranging from Critically Dry to Extremely Wet, based on total water yield (in acre-feet [ac-ft]) from October 1 through September 30. Total annual yields were plotted, ranked from highest to lowest, with symmetrical boundaries assigned to each water year type. A water year classification approach by the California Department of Water Resources could also have been used (Jeff Mount, personal communication 2006).

In some years, a large winter flood or period of very high winter baseflow can be followed by a low snowmelt runoff season. In this situation, the water year might be classified as Wet yet the snowmelt runoff would be more typical of a Normal water year. To determine how often this occurred, total annual yield was computed for the snowmelt runoff season only, designated as the *runoff year* (RY) from March 20 through August 10. Each water year was reevaluated by runoff year type using the WY designation procedure (Appendix C).

2.4.4. Selecting a Runoff Year for Each Classification

One runoff year was selected from each of the five runoff year types based on total yield, hydrograph shape, and availability of temperature data. WY2005 (Extremely Wet), WY1973 (Wet), WY1971 (Normal), WY1968 (Dry), and WY1976 (Critically Dry) were selected for ecological analyses described in later sections. Although identifying representative runoff years would have been best, the scarcity of water temperature records was a primary factor in selecting a runoff year for each classification. Therefore, the five annual hydrographs selected should not be considered representative of their respective runoff year classification, but rather one sample from each runoff year type.

2.4.5. Estimating Annual Maximum Flood Frequency Curves

Annual maximum flood frequency curves were generated from the instantaneous (15-minute) annual maximum discharges. For the Clavey River, 33 water years provided instantaneous annual maximum discharge data. Although the WY1997 flood occurred three years after the gage was discontinued, the USGS estimated the WY1997 peak discharge by extending the WY1995 rating curve, using flood debris and other high water marks. The USGS did not estimate peak discharges for WY1984, 1985, and 1986. After adding the WY1997 peak flood, a Log-Pearson Type III distribution was fit to the flood record using two methods: (1) the standard procedure established by the USGS (1982) and, (2) by eye. The fit-by-eye method was employed because the fit was closer than with the standard procedure.Annual maximum flood frequency curves were also generated for Cherry Creek, for its unregulated and regulated periods. Prior to flow regulation, flow was measured at USGS Gage No. 11277000, Cherry Creek near Hetch Hetchy, from WY1915 to WY1955; after flow regulation, flow was measured at USGS Gage No. 11277300, Cherry Creek below Valley Dam, from WY1957 to WY2005.

2.4.6. Reconstructing Historical Flood Timelines

To interpret aerial and ground photographs for bed mobility thresholds and effects on riparian vegetation, timelines of annual maximum peak flood recurrences were needed. For example, a 20-yr-old white alder as seen in a 1993 photograph; using a flood timeline, the flood magnitudes (measured as annual maximum flood recurrence intervals, in years) that the alder must have experienced can be estimated. These timelines required estimates of the flood recurrence of every annual flood peak from WY1960 to WY2005.

Although the 1N01 gaging station (Gage No. 11283500, Clavey River near Buck Meadows) record was extensive, some estimated instantaneous flood peak magnitudes were missing. To estimate the missing peak discharges, which leads to estimating annual maximum recurrence intervals, annual maximum floods were first estimated by scaling Clavey River flood peaks to the flood record of USGS Gage No. 11266500, Merced River at Pohono Bridge. This scaling technique is limited, given: (1) known differences in flood peaks when comparing earlier water years when both gages were operating, and (2) TID's hydrological modeling on the Clavey River, which also estimates flood peaks. However, most missing annual maximum floods, including those from WY2000 to WY2004, were relatively small (less than three-year floods), and therefore would not seriously affect the analysis.

2.4.7. Estimating Mobilization Thresholds for Depositional Features

Mobilization thresholds for depositional features were estimated using two approaches: (1) a bottom-up approach, where bed mobilization thresholds were estimated from basic hydraulic models, and (2) a top-down approach, where bed mobility thresholds are observed and/or inferred in the field. Both approaches were attempted to establish mobility thresholds for depositional features in the mainstem Clavey River.

By Hydraulic Models

Several analytical approaches were explored. Carling and Tinkler (1998) summarize investigations that evaluate mobilization processes of individual large rocks via rolling (pivoting) or sliding. They generalize that large boulders tend to mobilize when the Froude number (Fr) equals 1 and the associated critical depth (H_c) is at least equal to the height of the boulder (D_i). This method may apply to the largest boulders in a nested depositional feature, but not to the smaller particles nested within the larger boulders. These smaller particles are variably and hydraulically hidden among the larger boulders, such that the hydraulic forces acting upon these smaller particles are extremely variable. Analysis of sediment transport thresholds using the methods of Bathurst (1987) was attempted for individual patches at the Cottonwood Bar and the boulder sub-reach, but Bathurst's equation was not intended to be applied to individual depositional patches; results were unrealistic and so are not reported here.

A promising method to predict mobility and scour of these smaller depositional features was developed by Barta et al. (1994), and refined by Barta et al. (2000) (for details on Barta et al. 2000 methods, see Appendix D). In the Barta et al. (2000) methods, the mobility threshold of smaller depositional features is estimated by: (1) the upstream or downstream obstruction height responsible for their existence, and (2) the ratio of cross-sectionally averaged shear stress to critical shear stress, for the particle size of that patch. These relationships were developed from empirical data collected at streams on the east side of the Sierra Nevada, where obstruction heights are generally less than 3.2 ft (1 meter, m). These east side Sierran stream obstructions are smaller than those of the Clavey River mainstem.

The Barta et al. (2000) method was applied at locations within the Cottonwood Bar and boulder-bedrock sub-reach (Table 7). The relationships developed by Barta et al. (2000) to predict mobility and scour were useful in estimating mobility thresholds on these smaller deposits of particles within nested depositional features. However, the plots in Barta et al. (1994) and Barta et al. (2000) are small and the raw data could not be obtained from the first author. Therefore, pertinent charts from Barta et al. (2000) were scanned and fit to log paper, to re-create the predicted mobility threshold relationship. In spring 2005, cross section, slope, obstruction height, and particle size data were collected as needed to support this analysis (see Section 3.3). The Hydrologic Engineering Centers River Analysis System (HEC-RAS) model was run to predict the flow that could achieve the boundary shear stress necessary, defined as greater than three times the critical boundary shear stress for the D_{50}; shear stress was computed using the HEC-RAS water surface slope through the respective cross section, as described by Barta et al. (2000).

By Empirical Observation

Mobilization thresholds for depositional features were also estimated by empirical observation. Observation occurred in the field during tracer rock experiments (Section 2.3.4) and while comparing paired aerial and ground photographs before and after floods of known magnitude. Painted tracer rocks were set on the surfaces of depositional features, or in-situ rocks were painted and monitored for movement. Tracer rock and photo comparison observations were performed on the Clavey River and Cherry Creek mainstems.

Tracer rocks were generally set in rows and sized to represent the D_{50} and D_{84} particle size distribution of the depositional surface (refer to USFWS and HVT 1999 for details of field setup). Following a known flood peak, the tracer rocks were inventoried for movement. Peak flow thresholds for bed surface mobilization were estimated after several flood peaks were monitored by plotting the data (X axis as peak discharge and Y axis as percentage of tracer rocks mobilized). A percentage of tracer rocks mobilized has not been established in the scientific literature as a threshold for "significant" bed surface mobilization, although 50% has been used. Tracer rock data can also be used to calibrate hydraulic models,

To mobilize the D_{85} and D_{50} for the cobbles at the head of each bar, flows were predicted using the methods of Bathurst (1987) and Wiberg and Smith (1987).

2.4.8. Modeling Willow Species Initiation, Establishment, and Persistence

To quantitatively forecast initiation, establishment, and persistence for willow species on Cottonwood Bar, their life and death processes were considered in a modest spreadsheet model. This model was applied to Arroyo willow (*Salix lasiolepis*), Jepson willow (*Salix jepsonii*), and dusky willow (*Salix melanopsis*) because they all have short-lived seeds released during the snowmelt hydrograph; the model was not applied to white alder (*Alnus rhombifolia*) due to its long seed dispersal period and viable seed longevity. This model is similar to the recruitment box model (Mahoney and Rood 1998) that combines inundation

Table 7. Summary of depositional features on the Clavey River targeted for analysis using methods of Barta et al. (2000).

Cross section	Type of deposit	Obstruction used for height measurement
12+60	Obstruction	Downstream
16+33	Obstruction	Downstream (smaller)
16+33	Obstruction	Upstream (larger)
17+53	Lee	Upstream
32+10	Lee (cobble)	Upstream
32+10	Lee (small gravel)	Upstream
35+37	Lee	Upstream
35+67	Lee	Upstream
37+11	Lee	Upstream
37+39	Obstruction (center of channel)	Downstream
37+39	Lee (right bank)	Upstream

timing of germination surfaces, seed release timing, and rate of flow recession. Modeled results were then compared to ground photographs of Cottonwood Bar taken in WY1993, WY2000, and WY2005, and an aerial photograph in WY1988.

An early task was to complete a woody riparian tree phenology for each willow species for the Clavey River study site. The phenology study allowed us to estimate when/if seeds of each willow species are settling onto Cottonwood Bar.

To germinate and then grow roots, a fallen willow seed needs to settle on sufficiently moist substrate. A stage-discharge rating curve at XS 16+33 was developed from the stream gaging and field surveys. Shallow groundwater elevation was assumed to mimic this stage-discharge relationship. A one-foot-thick capillary zone extending above the groundwater surface was estimated from the literature and observed in the field. Therefore, the bar surface was considered sufficiently moist when the shallow groundwater table came within one foot of the bar surface. This capillary zone model resulted in an all-or-none assessment;

soil moisture either promoted germination and root growth or killed the seedling. Capillary zone elevation could have been measured by periodic monitoring of piezometers, and would have eliminated the need for the linear one-foot-thick capillary zone assumption. Given the pilot study nature of the project, piezometers were not installed.

To model establishment and persistence of willows in the spreadsheet, cross sections XS 16+33 and XS 32+62 were simplified by selecting discrete flat surfaces along the cross section (Figures 12 and 13). Wetted bar surface and sub-surface were modeled for each sample runoff year's snowmelt hydrograph. In the spreadsheet model, seeds landing on wetted surfaces germinated, then required a minimum rate of mainstem stage decrease, allowing germinated seedlings to successfully maintain root extension; root extension was assumed to be 0.5 inch (in)/day (0.04 ft/day) to 1.0 in/day (0.08 ft/day) for all willow species (Mahoney and Rood 1998). The minimum rate of stage decrease had to continue until early fall for willows to be considered "initiated" in the model.

Seedlings can be initiated, only to be scoured by peak flows in their first winter. Peak flow thresholds that would scour seedlings in their first winter were estimated for each discrete surface by examining the annual hydrographs, to model whether seedlings that did survive to early fall would have been scoured away by winter floods. Seedlings that survived the winter floods and peak flows of their second snowmelt peak were considered by the model to have successfully achieved early establishment.

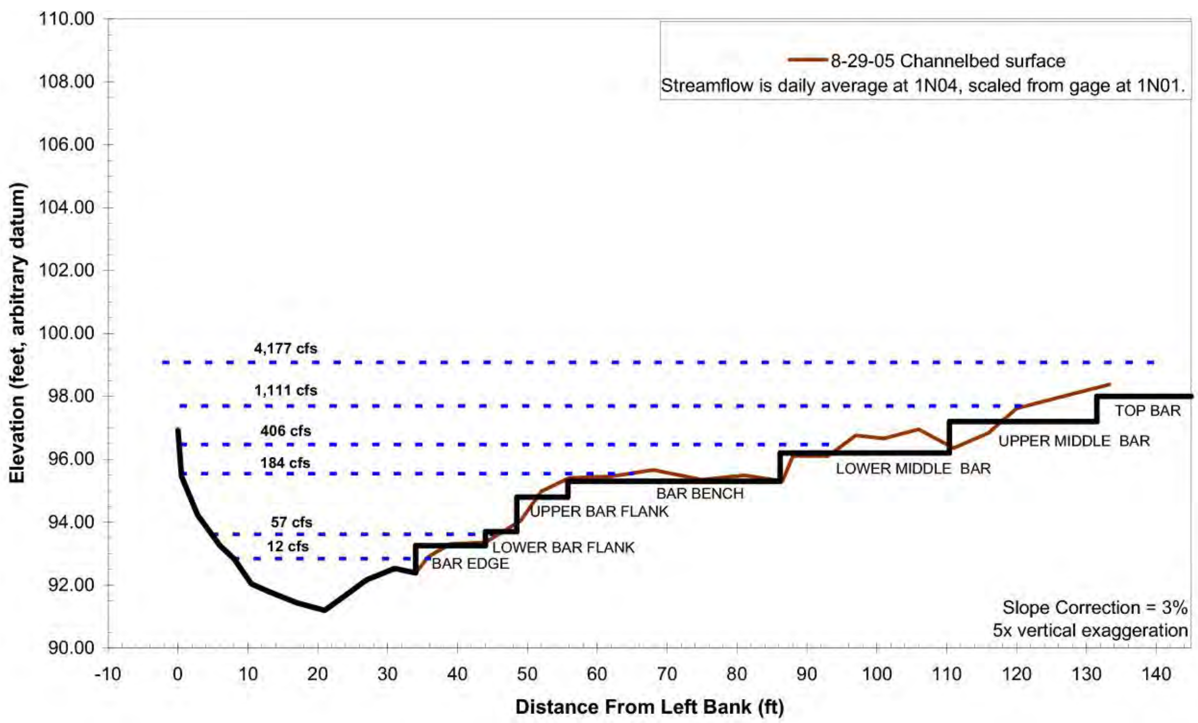


Figure 12. Clavey River Cottonwood Bar, cross section 16+33, used to model willow seedling initiation and early establishment.

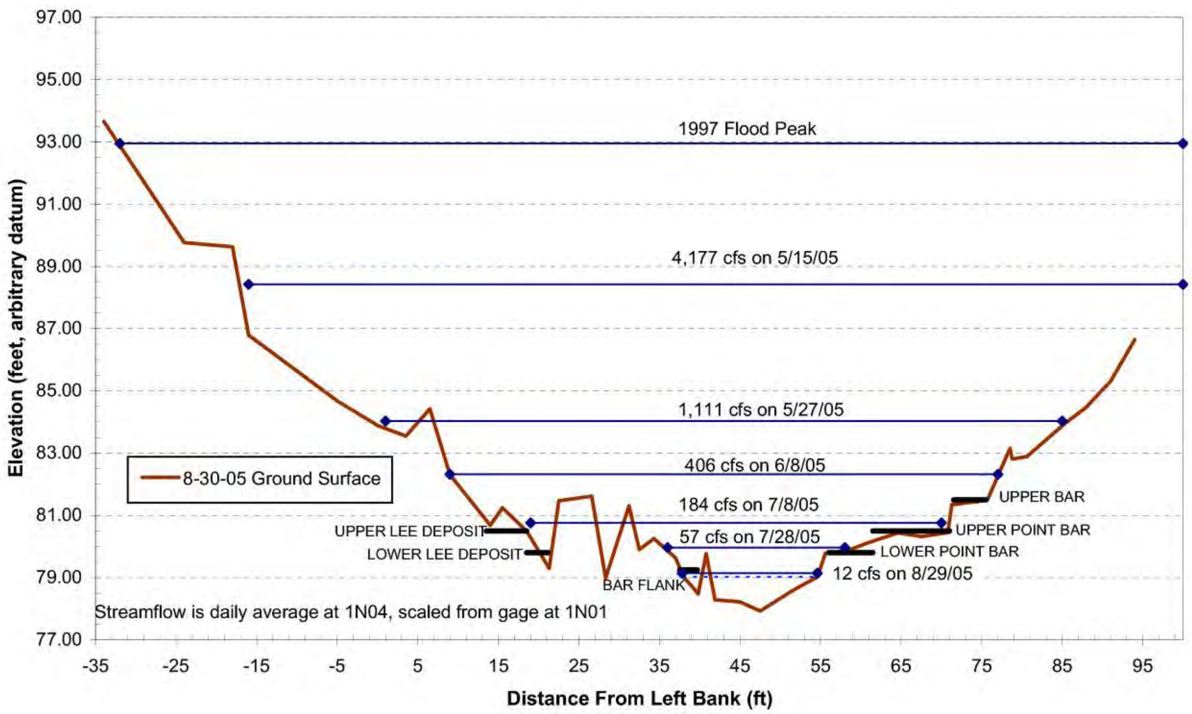


Figure 13. Clavey River, small point bar between boulder ribs, cross section 32+62, used to model willow seedling initiation and early establishment.

2.5. Synthesis for Formulating Example Pulse Flow Guidelines

Annual snowmelt flows heavily influence fish, amphibian, and benthic macroinvertebrate habitat area and quality. The project sought quantitative relationships between habitat area and daily average streamflow for many aquatic and riparian species. If these relationships could be established, example pulse flows guidelines could be formulated. In this project, relationships were frequently quantified graphically (Figure 14).

Expert habitat mapping of a life stage for each targeted species was used to generate *habitat rating curves*; these habitat rating curves represent a nonlinear relationship between daily streamflow (cfs) on the X-axis and habitat availability (ft^2) on the Y-axis. For the Clavey River, two sets of habitat rating curves were constructed for: (1) the Cottonwood Bar sub-reach (STA 13+90 to STA 17+75), which is representative of a bar-scale biological hotspot, and (2) the remaining three boulder-bedrock sub-reaches combined (collectively referred to as the *boulder sub-reach*), which is representative of a confined mainstem channel with few large depositional features. For Cherry Creek, two sets of habitat rating curves were also constructed for: (1) Cherry Bar, and (2) the boulder sub-reach. Each habitat rating curve was defined by five points corresponding to the five flows at which habitat was mapped (ranging from 12 cfs to 1112 cfs). The line formed by the five points was assumed to be smooth (i.e., the points were connected by straight lines). For flows less than 12 cfs (the lowest streamflow habitat mapped), habitat area was assumed to decrease linearly to 0 cfs.

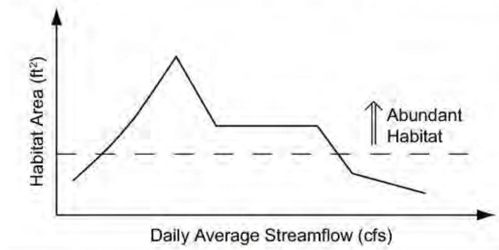
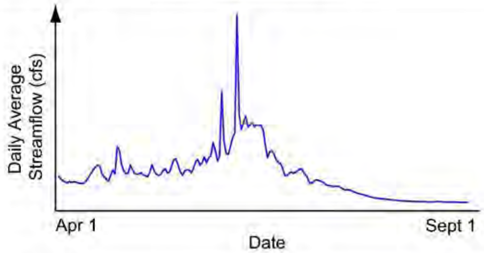
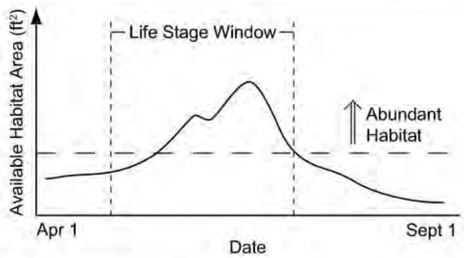
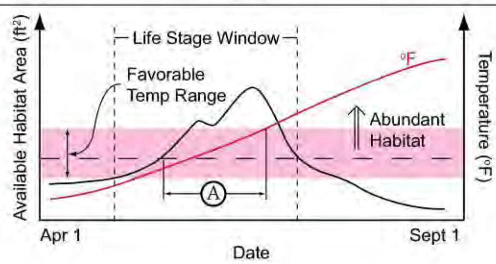
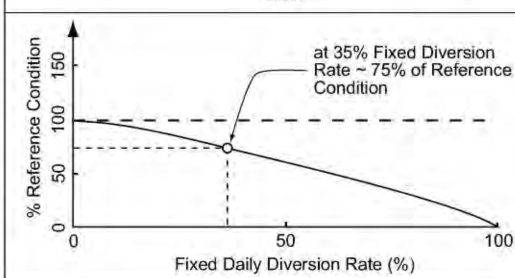
From the habitat rating curve (Figure 14), each streamflow can be associated with a quantity of good habitat as estimated by EHM. Each day's streamflow during the snowmelt hydrograph for a selected runoff year, therefore, can be assigned an area of good habitat. A *habigraph* portrays the daily amount of habitat available each day during the snowmelt hydrograph, with available habitat (ft^2) on the Y axis and day of the snowmelt hydrograph on the X axis. For the snowmelt hydrograph (April 01 through September 30) in the five selected runoff year types, habigraphs were generated for each species and life stage habitat mapped in WY2005.

As stated previously, validation of available habitat area as a function of species density or population was not performed. Use of available habitat area as a proxy for species density or population is a simplifying assumption in keeping with the scope of this project. Factors other than habitat availability could be limiting (for example, species interactions such as predation).

Available habitat area is based primarily on flow characteristics (velocity and depth), channelbed composition, and cover considered in EHM, but water temperature, species life stage timing, and species temperature thresholds also determine whether species actually use, and their populations benefit from, that habitat. Individuals will prosper only if water temperatures are favorable, and the population will prosper only if abundant habitat occurs when needed by each life stage. Therefore only portions of the habigraphs provide everything ecologically necessary and relevant for a particular species (Figure 14). For example, abundant rainbow trout fry habitat in August occurs outside the late-spring through early-summer period when fry are in the river. Even if water temperatures were favorable, abundant fry habitat in the habigraph during August would not be ecologically necessary or relevant.

To prescribe pulse flow guidelines, the relationship between ecologically necessary/relevant habitat and streamflow was established over snowmelt hydrographs representing the five runoff year types. To qualify as ecologically necessary and relevant habitat (referenced in this report as *ecologically available habitat*), each day's habitat in a given species/life stage habigraph had to: (1) occur within the time period for that life stage, (2) fall within the favorable temperature range, and (3) be relatively abundant (Figure 14). The first two qualifiers were determined from the scientific literature, while the third was estimated from the habitat rating curves (streamflows providing 60% to 80% or more of peak habitat abundance on the habitat rating curve). For a particular species life stage, a Wet runoff year might have 50 days when all three qualifiers were met, whereas a Dry runoff year might have only 20 days.

A computed *reference condition* was the number of days in a particular runoff year's habigraph in which all three habitat qualifiers for a specific species and life stage were met under unregulated streamflows. Under varying managed flow scenarios (e.g., fixed daily diversion rates), the number of qualifying days might remain unchanged (remain at 100% reference condition), increase, or decrease. The computed reference condition was expressed as a percentage: the number of qualifying days in the unregulated habigraph as the

Single Species Life Stage X in Water Year Z	Name	Data Required and Origin
	Habitat Rating Curve	"Good" habitat area for that species life stage, at various flows Expert habitat mapping
	Annual Snowmelt Hydrograph	Daily average flow at each day of the runoff year (April 1 to Sept 1) for a particular runoff year type USGS gaging station
	Habigraph	Habitat area for species life stage, and day of the runoff year for a particular runoff year type Habitat rating curve and snowmelt hydrograph
	Habigraph with Temperature Thresholds & Life Stages Periodicity	Dates of species life stage window, water temperature, life stage temperature thresholds Thermographs and scientific literature (A) Number of days with abundant and good habitat for Life Stage X in unregulated Water Year Z. This becomes the Reference Condition for Water Year Z.
	Reference Condition Curve	Number of days with ecologically available area, desired snowmelt flow diversion rate in percent Annual habigraphs, habitat rating curve

$$\text{Reference Condition (RC)} = \frac{\text{\# Days Ecological Habitat @ Diversion Rate} = N}{\text{\# Days Ecological Habitat Reference Condition}} \times 100$$

Figure 14. Important physical and biological graphical relationships for recommending pulse flows.

denominator and the number of qualifying days in a habigraph created under a specific managed snowmelt hydrograph as the numerator. In this study, reference condition curves have the percent reference condition on the Y axis and the daily diversion rate on the X axis (Figure 14). With greater diversion rate of the snowmelt hydrograph, the likelihood of diverging either negatively or positively from the 100% reference condition increases. The ecological goal for prescribing pulse flows would be to recommend diversion rates that diverge from the reference condition as little as possible.

3.0 Results

3.1. Hydrologic Analyses

3.1.1. Snowmelt Hydrograph by Water Year Type

As described in Section 2.4, flow data for the Clavey River and Cherry Creek were organized so that annual hydrographs could be constructed from WY1960 to WY2005. Water years were classified into five types, ranging from Critically Dry to Extremely Wet, based on total water yield (ac-ft) from October 1 through September 30 (Appendix C). Runoff years were classified into the same five types, but based on water yield (ac-ft) from April 1 to August 31. One runoff year was selected from each of the five runoff year types, based on yield, hydrograph shape, and availability of temperature data. Snowmelt hydrographs were generated from the selected runoff years (Figure 15).

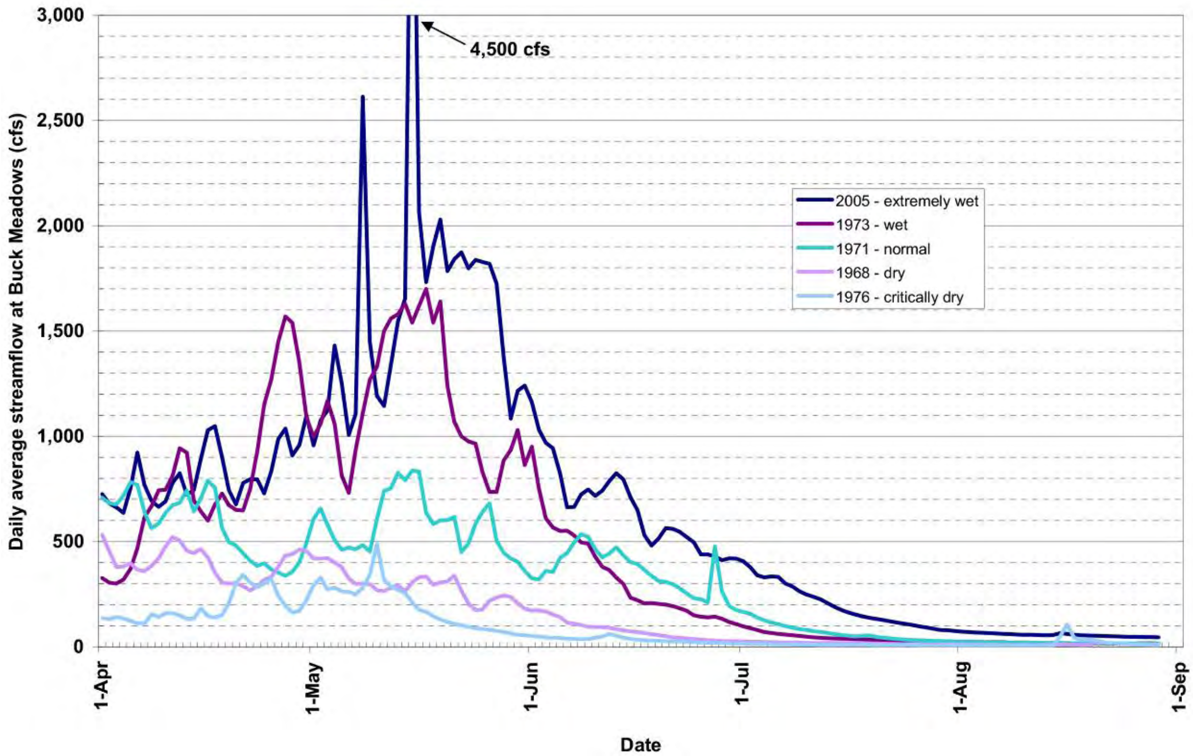


Figure 15. Annual snowmelt hydrographs of selected runoff year types, from USGS Gaging Station No. 11283500, Clavey River at Buck Meadows.

3.1.2. Annual Recurrence Curves of Daily Average Flow

Snowmelt floods are distinct from winter floods; snowmelt flood peaks generally are lower in magnitude, longer in duration, and often exhibit several smaller peaks. The distinctions become evident when fitting Log-Pearson Type III distributions to the greatest daily average flow from each water year versus from each annual snowmelt hydrograph (Figure 16). For example, a 20-yr annual daily average peak flow is approximately 12,000 cfs (solid blue line, Figure 16) whereas the 20-yr daily peak during snowmelt runoff (post-April 1) is approximately 5000 cfs (dashed blue line, Figure 16). The largest recorded daily average snowmelt peak is 10,300 cfs in WY1982 and has a snowmelt runoff recurrence > 100-yr, yet a peak instantaneous annual maximum flood of 10,300 cfs (a winter flood) has only a 6-yr to 7-yr recurrence. A simple ranking of snowmelt daily average peaks (from highest to lowest) demonstrates that larger snowmelt peaks occur later in wetter snowmelt seasons (Appendix C).

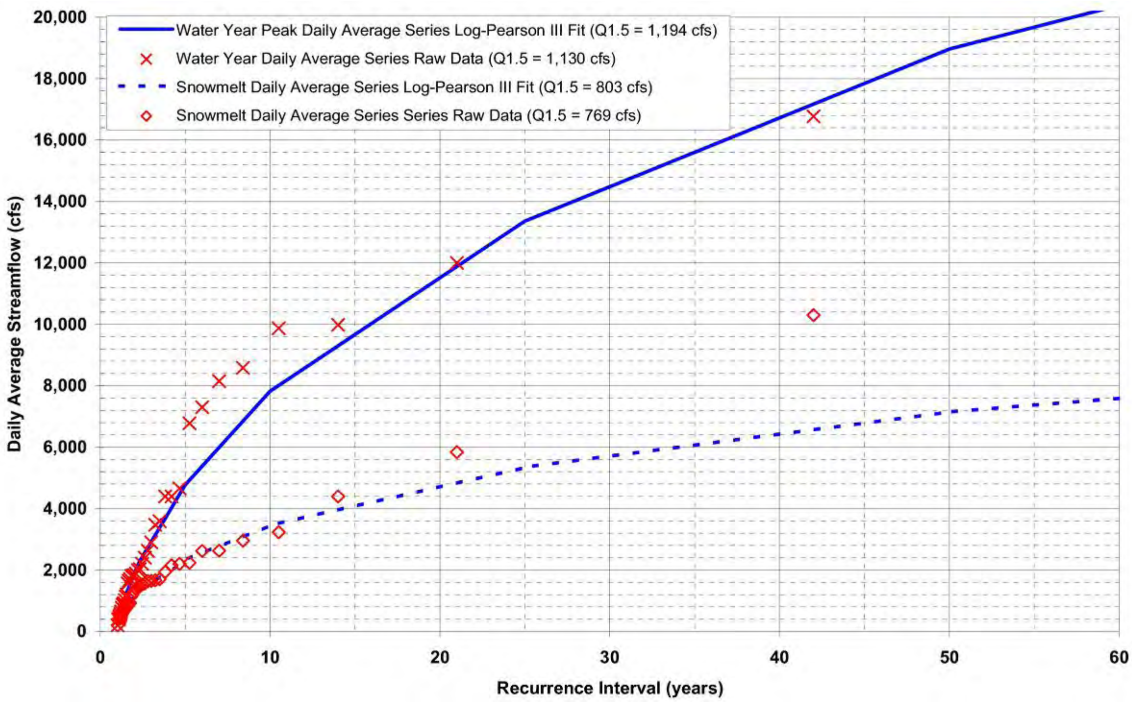


Figure 16. Annual recurrences of peak daily average streamflow during the entire water year and during the snowmelt runoff period for the Clavey River.

3.1.3. Snowmelt Hydrograph Recession Limb

The annual snowmelt recession limbs were graphed for the data available (RY1960 to RY1999, and RY2005) (Figure 17). No pattern in flow timing, duration, or magnitude is apparent; the graph is chaotic and the primary characteristic is variability.

To focus on the effects of flow variability, duration, and magnitude, the timing of seasonal variation was eliminated by standardizing each annual snowmelt recession limb to begin on Day = 1 rather than on its actual calendar date. Once timing is standardized, the snowmelt recession limbs indicate that flows are greater and last longer in wetter runoff years (Figure 18). Wet runoff years are seen to exhibit higher streamflows near the ends of their slow recession limbs, than drier runoff years (i.e., in Figure 18, light and dark blue lines are generally above and to the right of red and orange lines). By mid-summer, each year's snowmelt recession limb appears to merge into similar summer baseflows (Figure 18).

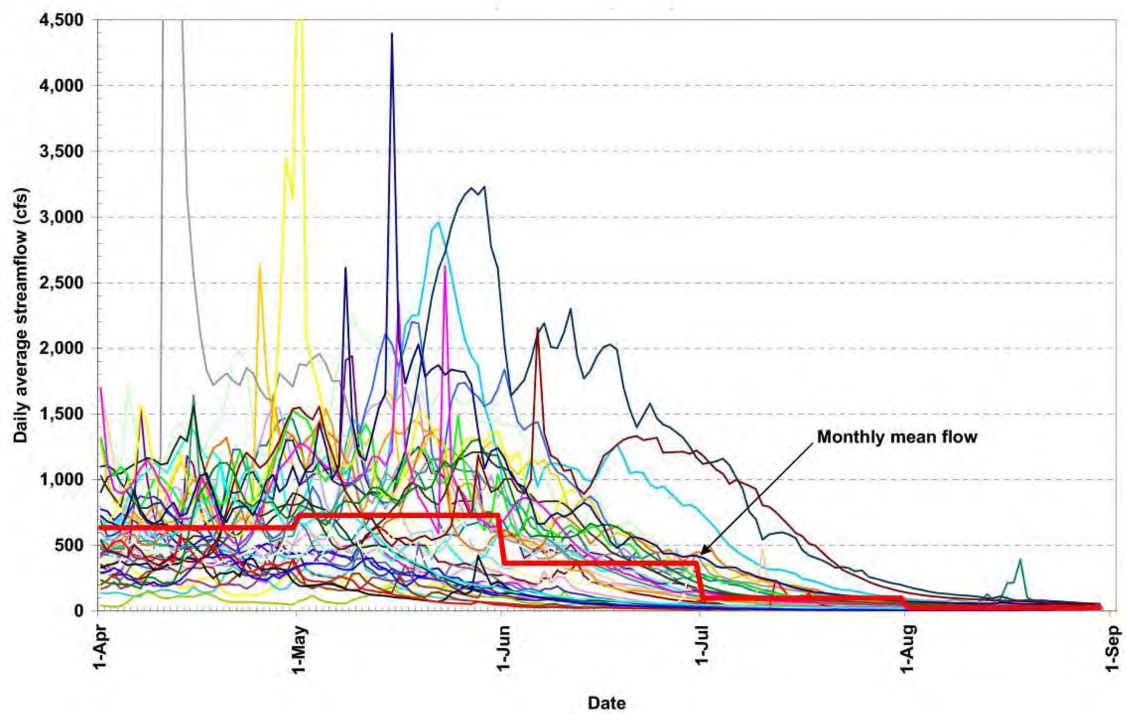


Figure 17. Annual snowmelt recession limbs of the annual snowmelt hydrograph for runoff years RY1960 to RY1999, and RY2005, for the Clavey River.

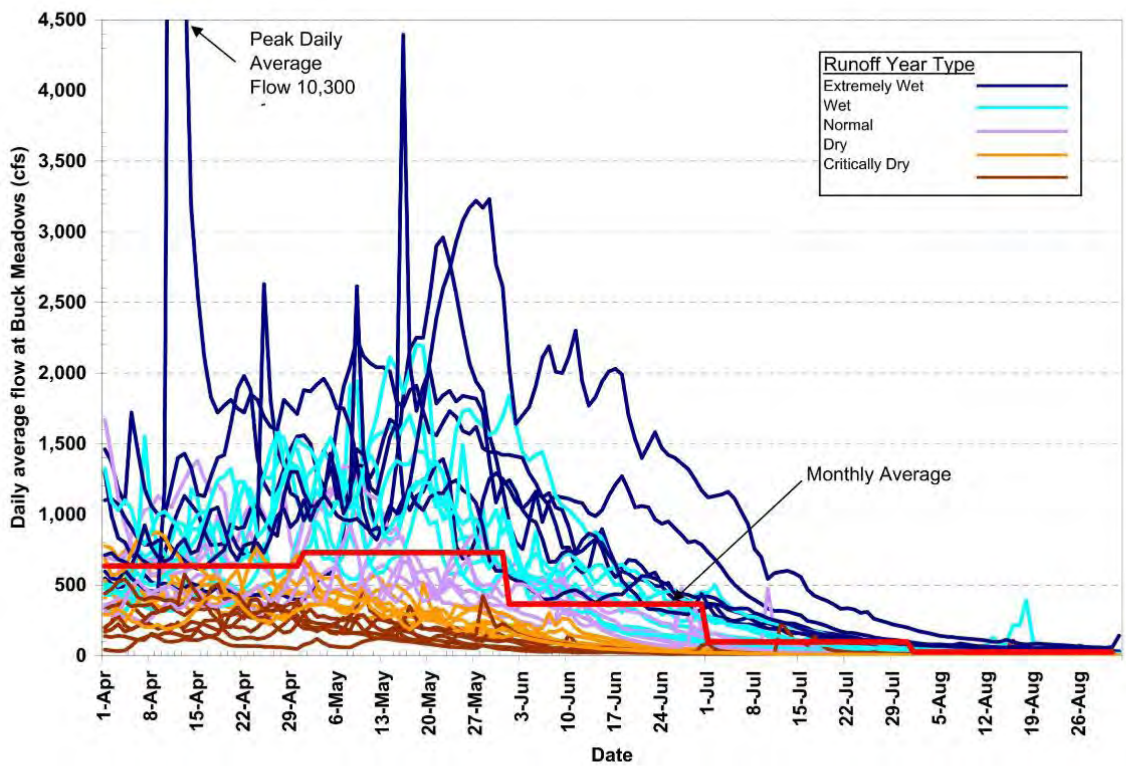


Figure 18. Standardized annual snowmelt hydrograph recession limbs for runoff years RY1960 to RY1999, and RY2005, grouped by RY type for the Clavey River.

A distinctive feature of the snowmelt recession limb is a break in slope, transitioning from a rapidly declining recession limb to a more gentle recession limb (Figures 3 and 19). The flow at which this transition occurs is called the *snowmelt recession node.* The node was identified by fitting straight lines through the rapidly declining and gentler declining recession limbs and recording their intersection. No formal criteria were developed for fitting rapid and gentle recession lines (i.e., it was done by eye). However, as expected, in wetter runoff years the node was farther to the right, indicating that flows were greater and occurred later in wetter runoff years (Appendix C). Consequently, readers can match annual snowmelt recession nodes (Appendix C) to each annual hydrograph (scaled to the Clavey River study site).

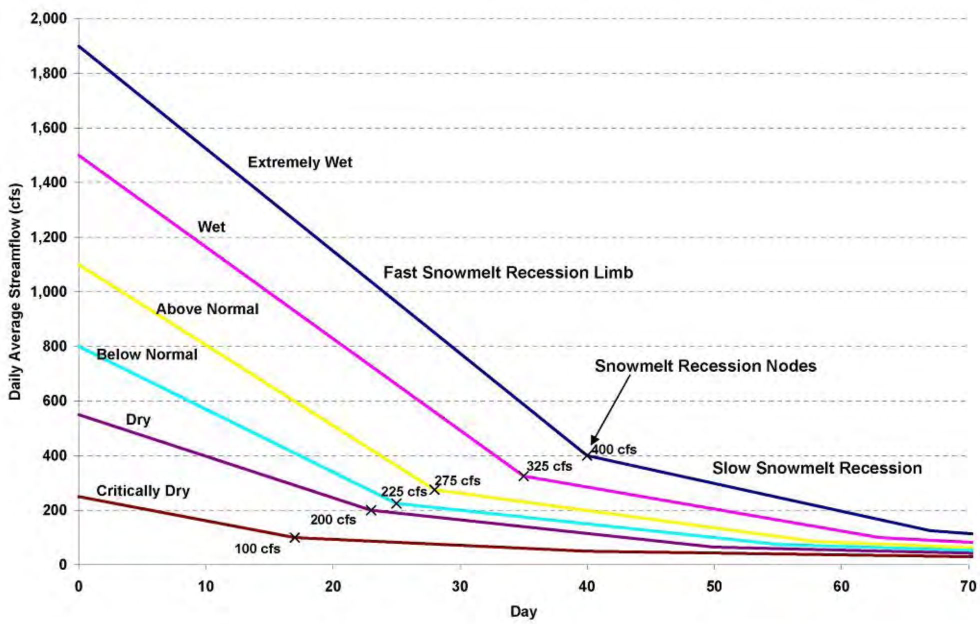


Figure 19. Generalized snowmelt recession limbs and recession nodes by RY type for the Clavey River.

The rapidly declining and gently declining recession limbs can be physically explained by changes in the primary snowmelt runoff pathway throughout the watershed. During high rates of snowmelt, runoff may be primarily overland, which would reach the stream faster than subsurface flow. A consequence of these pathways could be unique 24-hour (hr) patterns in streamflow variation: the rapid snowmelt recession limb should exhibit wider 24-hr fluctuation due to more variable surface runoff pathways off the landscape; the slow recession limb might exhibit a more subdued 24-hr fluctuation due to the relative and local homogeneity of sub-surface pathways.

The project did not further explore snowmelt recession pathways and their potential management applications. The utility of a third recession limb, the snowmelt-to-summer-baseflow transition limb, which follows the gently declining snowmelt recession limb, also merits further investigation.

3.1.4. Snowmelt Stage-o-graphs

While the snowmelt recession hydrograph is an important tool for ecological investigations, the snowmelt recession flow's water surface elevation (stage) over time is equally important. Graphs of the snowmelt flow's surface elevation over time were generated and called *stage-o-graphs.* Animals and plants generally do not respond directly to cfs; they respond to changes in velocity, surface area, water temperature, and depth—but none of these physical habitat variables are linearly related to streamflow. Changes in water surface elevation for particular streamflows are functions of a channel's cross-sectional area, slope, local hydraulic controls, and roughness conditions. Two example snowmelt stage-o-graphs were prepared for the Cottonwood Bar cross sections XS 16+33 and XS 32+62 (Figure 20). The sub-reach at XS 16+33 is wider and less steep than at XS 32+62, and is less sensitive to streamflow changes (relative to stage change) than the narrower and steeper boulder sub-reach represented by cross section XS 32+62. Stage differences of up to one foot, but resulting from the same snowmelt hydrograph, can have significant ecological consequences.

Figure 20. RY2005 snowmelt stage-o-graphs for a point bar (cross section XS 16+33) and for a narrower, boulder-bedrock channel (cross section XS 32+62), for the Clavey River.

3.1.5. Annual Maximum Flood Frequency Curves

As estimated by the USGS, the Clavey River's largest flood of record was 47,000 cfs in January 1997, based on 34 years of data from the 1N01 gage (USGS Gage No.1283500 near Buck Meadows at the 1N01 Bridge). Because the database is 34 records, when plotting the raw data, the recurrence interval of the 47,000 cfs January 1977 flood is 34 years (Figure 21). However, using the Log-Pearson Type III distribution, this flood corresponds to a recurrence interval of approximately 77 years (Figure 21). Based on data from 88 years of data on the Merced River at Pohono Bridge (USGS Gage No. 11266500), the January 1997 flood event had a Log-Pearson III recurrence interval of approximately 103 years. In subsequent analyses in this report, the 1997 flood is considered to be a 75-yr event.

A similar analysis was performed to generate an annual maximum flood frequency curve for Cherry Creek. The annual maximum flood frequency curve for the unregulated flows was developed using data from USGS Gage No. 11277000, Cherry Creek near Hetch Hetchy, from WY1915 to WY1955; after regulation, the curve was developed using data from USGS Gage No. 11277300, Cherry Creek below Valley Dam, from WY1957 to WY2005 (Figure 22).

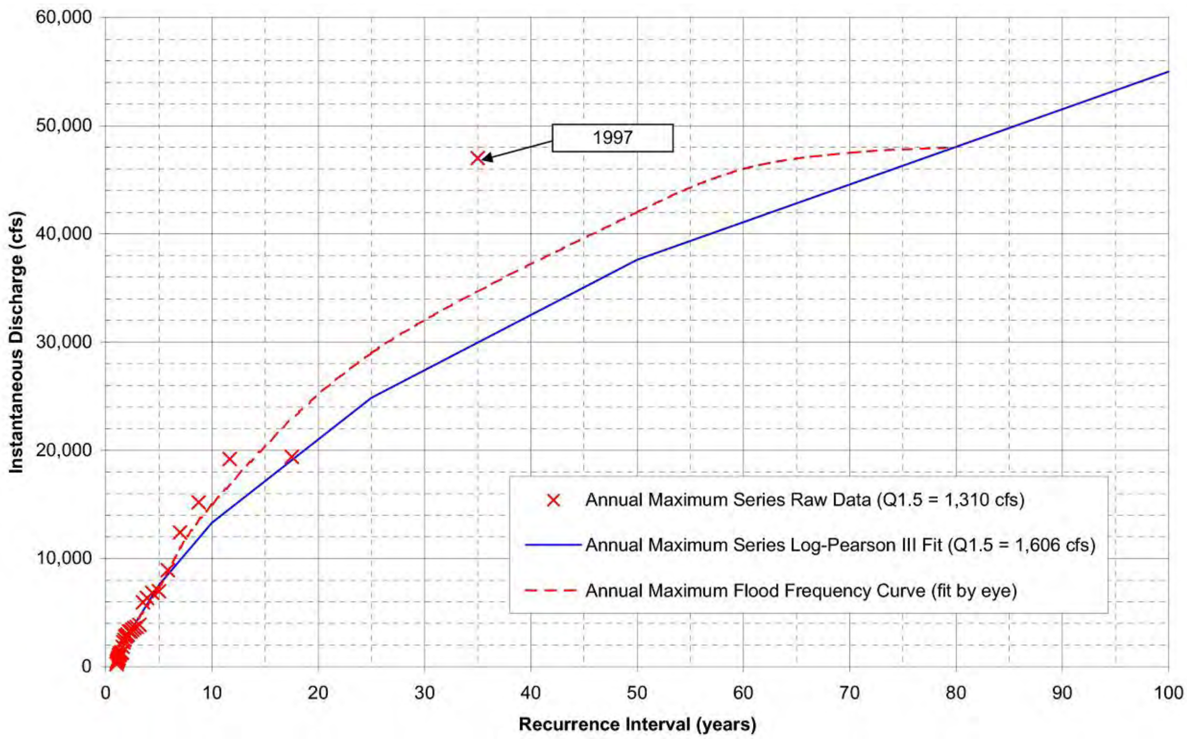


Figure 21. Annual maximum flood frequency curve with a 34-year record, from USGS Gaging Station No. 11283500, Clavey River at Buck Meadows.

3.1.6. Historical Flood Timelines

As described in Section 2.4.6, historical flood timelines were constructed for the Clavey River and Cherry Creek (Figures 23 and 24). For the Clavey River, each year's peak flow can be associated with its recurrence (for example, the highest flow in WY1980 had a recurrence of approximately 17 years) (Figure 23). In some water years, the snowmelt peak was the highest flood; these are indicated by the white bars in Figure 23. Also as described in Section 2.4.6, data from the Merced River at Pohono Bridge was scaled to estimate peak flows on the Clavey River (see hatched bars, Figure 23).

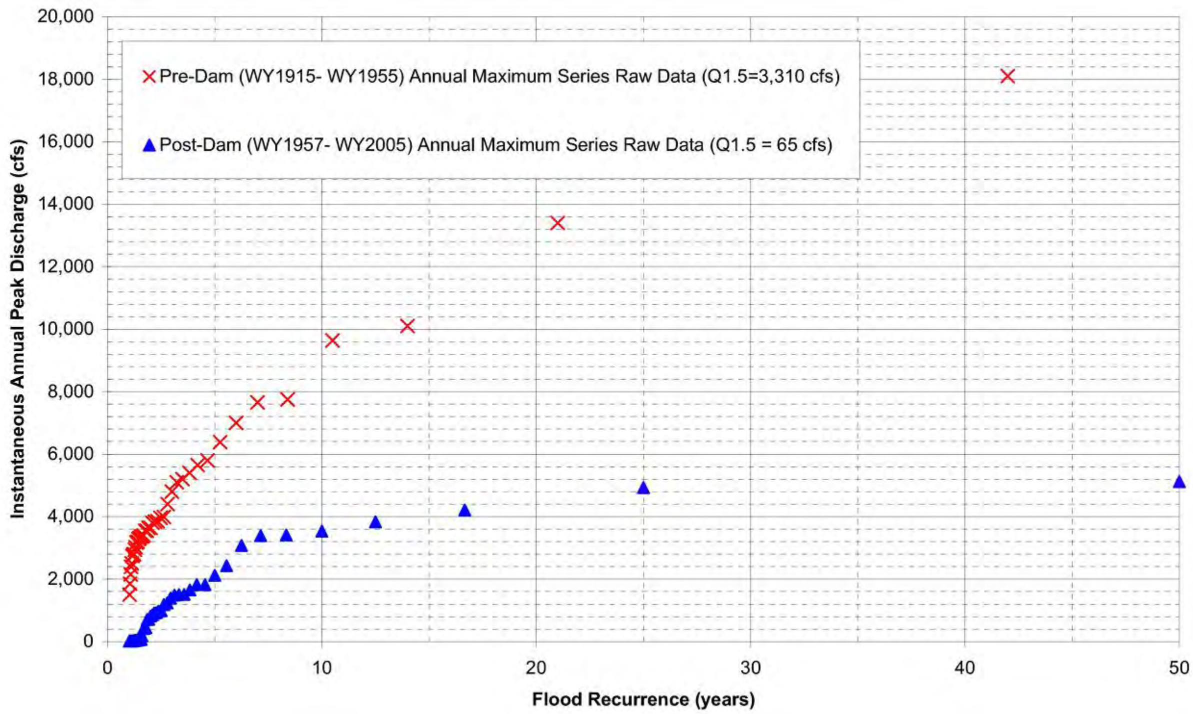


Figure 22. Annual maximum flood frequency curves prior to flow regulation at USGS Gage No. 11277000 Cherry Creek near Hetch Hetchy from WY1915 to WY1955, and after flow regulation at USGS Gage No. 11277300 below Valley Dam from WY1957 to WY2005.

The WY1986 annual maximum flood was estimated in the field, and was reported to be a 12-yr event (IRE 1994); this is in contrast to the approximate 5-yr to 7-yr estimate for the Merced River from its annual maximum flood frequency curve. The field estimate for peak WY1986 discharge, made in 1993, assumed the prominent debris line on several cross sections was made by the WY1986 flood, a water year with high flooding around much of Northern California. However, just a few years earlier in WY1980 and WY1982, the Clavey and Merced rivers experienced large floods. The magnitude of a 12-yr recurrence flood assigned to WY1986 (IRE 1994) was similar to the USGS flood magnitude estimated for the WY1980 peak flood. The debris line for the WY1997 peak flood was surprisingly easy to locate in WY2005; its shape and appearance were distinct and fresh. The summer field survey in WY1993 could have located the WY1980 peak and not the WY1986 peak debris line. In addition, TID's estimate for the WY1986 annual hydrograph indicates a much larger winter flood peak with a flood recurrence interval considerably greater than seven years. Further, shortly after the 1986 flood, fish survey crews observed considerable channel movement. The 12-yr annual maximum recurrence for the winter WY1986 flood was therefore assumed.

Creation of an historical flood timeline for Cherry Creek (Figure 24) was straightforward because USGS gaging records were obtained and the annual peak discharge was reported for each water year.

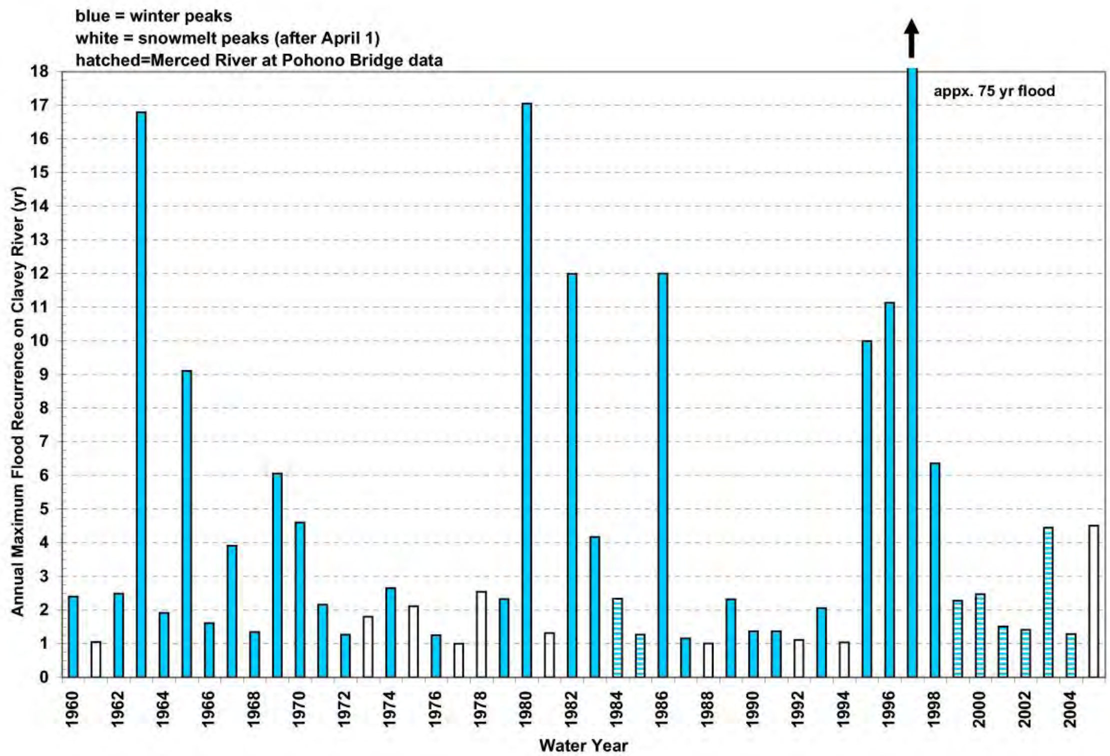


Figure 23. Clavey River historical flood timeline from WY1960 through WY2005.

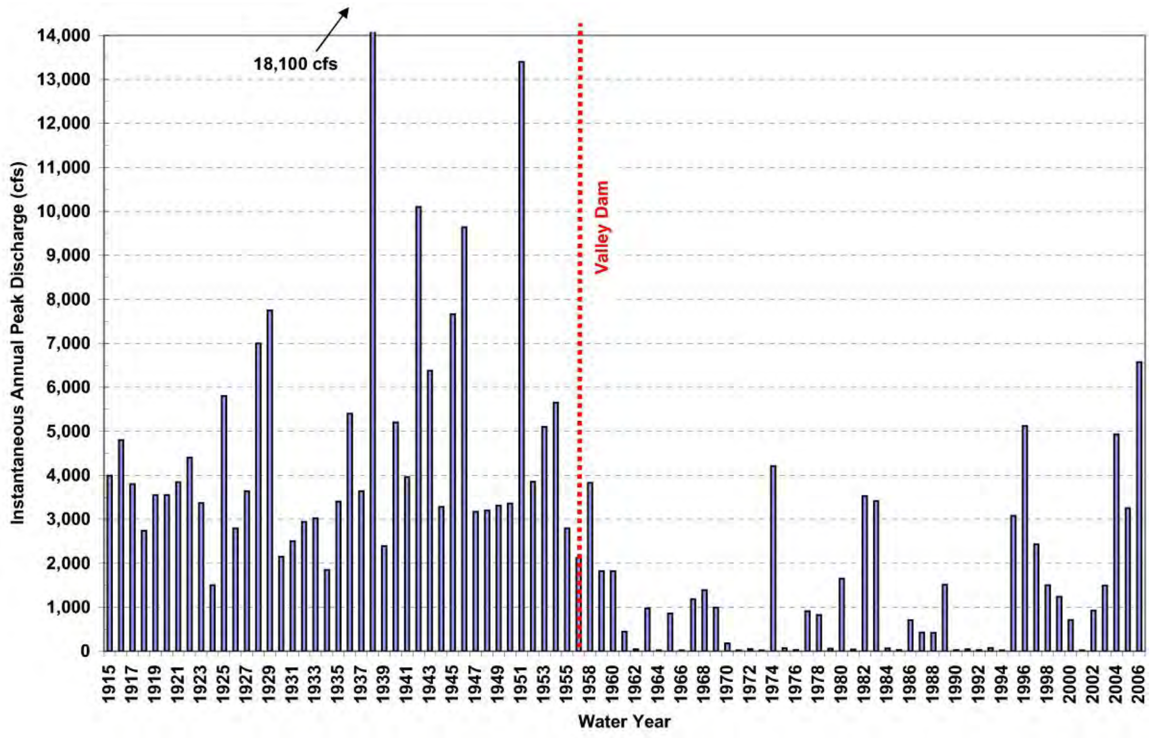


Figure 24. Cherry Creek historical timeline from WY1915 through WY2006.

3.2. Geomorphic Mobilization Thresholds Analyses

Flows mobilize bed surfaces and initiate coarse sediment transport; identifying these flow thresholds is fundamental to quantifying how annual hydrographs affect channel morphology in alluvial and bedrock rivers (USFWS and HVT 1999). In alluvial rivers, flow thresholds that mobilize many depositional features occupy a relatively narrow range (e.g., 1.2-yr flood to 5-yr flood). Boulder-bedrock rivers are often erroneously assumed to be sediment transport zones lacking depositional features. However, boulder-bedrock rivers exhibit nested depositional features, ranging from large boulder ribs down to lee sand deposits. When assessing bed mobility on steep boulder-bedrock rivers, their much greater range of particle sizes (large boulders to fine sand) must be considered, so particle sizes must be clearly targeted for predicting mobilization. Nested depositional features in a boulder-bedrock river should require a much wider range of threshold flows for mobilization (e.g., 1.2-yr flood to 100-yr flood) than in alluvial rivers.

Bed mobility and bedload transport thresholds in alluvial rivers have received considerable attention during the past 70 years, using field experiments (e.g., tracer rocks), bedload transport data (e.g., Parker et al. 1982), and analytical methods (e.g., Wiberg and Smith 1989). The alluvial river particles' overall smaller sizes and size ranges allow the hydraulic forces acting on these particles to be reasonably computed. But in steep boulder-bedrock rivers, with particle sizes ranging up to house-sized boulders, the acting forces are more complex than lift and drag forces (flow separation, particle sliding) making the hydraulics more complex (local critical flow, standing waves). Analytical approaches have been attempted to predict bed mobilization thresholds in boulder-bedrock channels (e.g., Bathurst 1987; Carling and Tinkler 1998), but the accuracy of these predictions lags behind that of alluvial river predictions.

Classification of nested controls and depositional features helped to categorize differential mobility thresholds for the mainstem Clavey River. However, a reasonably accurate analytical approach to predict bed mobilization thresholds in steep boulder-bedrock channels does not yet exist.

Therefore, empirical and analytical approaches were combined to determine flow thresholds that would mobilize bed surfaces and initiate coarse sediment transport. First, depositional features were classified so scientists and managers would use a common vocabulary. Second, analytical modeling of bed mobility was attempted, so that results could be compared with observed bed mobility thresholds. Next, bed mobilization was investigated by tracer rock experiments. Finally, bed mobility thresholds were estimated from sequences of aerial and ground photographs. The following sections describe the results of these analyses.

3.2.1. Classification of Depositional Features

Each type of depositional feature found was photographed, described, and classified (Appendix B). Classification allowed better visualization of the nested nature of these depositional features.

Wider and less steep channel segments tended to have more diverse and larger depositional features. A good visual perspective of nested depositional features can be seen in the panoramic photograph of the Clavey River mainstem looking downstream at cross section XS 35+67 (Figure 25). The channel width in the foreground (upstream of the cross section tape) becomes narrower downstream, to the prominent dark gray bedrock outcrop (with the appearance of a giant boulder) on the left bank and light gray bedrock outcrop on the right bank visible within the riparian trees. Downstream of this channel constriction, the channel appears to drop off sharply. One large boulder rib connects the opposing bedrock outcrops, while another upstream rib of smaller boulders angles upstream toward the right bank. Just upstream of the photograph is another boulder rib. The channel slope above the constriction is less than downstream, giving the appearance of the channel dropping off.

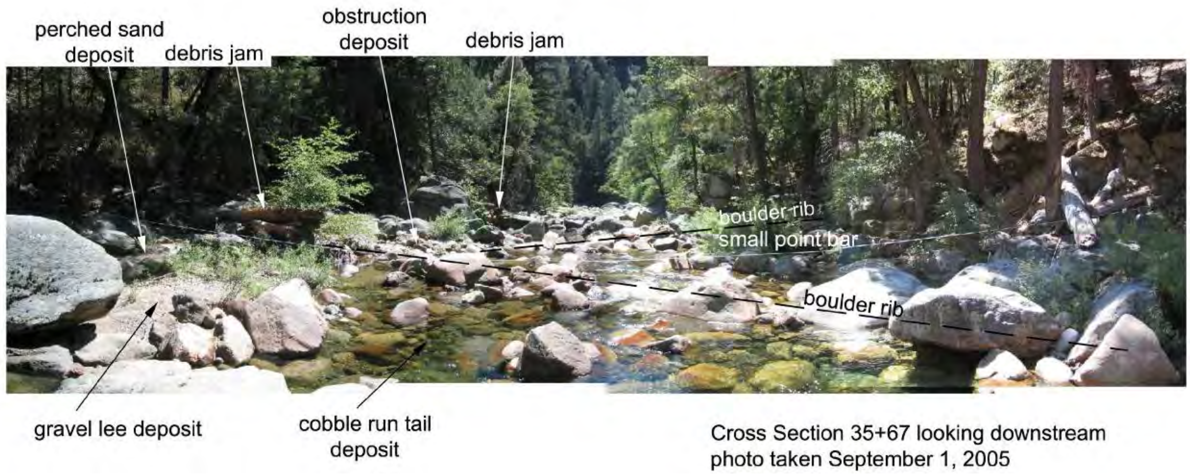


Figure 25. Panoramic photograph of the Clavey River mainstem, cross section XS 35+67, looking downstream.

This constriction functions as a primary hydraulic control. The boulder ribs upstream, which are composed of smaller boulders, are influenced by the primary control below, and in turn, exert a secondary hydraulic influence. Several depositional features depend on the boulder ribs: a small boulder point bar on the right bank, a small boulder/large cobble obstruction bar on the left bank, a perched sand deposit on the left bank, and a gravel/small cobble lee deposit on the left bank and right bank (Figure 25). Also along the left bank is a large woody debris jam with a lee cobble bar, overtopped by a deposit of sand and small gravel. Last, a cobble run tail deposit is at the cross section's thalweg.

3.2.2. Modeled Bed Mobility of Depositional Features

Using the three methods of Barta et al. (2000) that are based on relative shear stress (τ_b/τ_c) and relative obstruction height (H/D_{90}), a predictive model was employed to estimate bed mobility for depositional features in the mainstem Clavey River (Table 8) (Appendix D). In summary, to mobilize depositional features, predicted flow thresholds were much lower than flow thresholds supported by field observation (Section 3.2.3). Of the three methods (indicated by Equations 4, 5, and 6 in Table 8), the simple method of predicting critical

Table 8. Summary of flow thresholds for bed mobility in depositional features on the Clavey River, using three methods from Barta et al. (2000).

Cross section	Station	D_{50} (mm)	D_{90} (mm)	Obstruction height (ft)	Prediction using Equation 4 (high uncertainty)	Prediction using Equation 6 (high uncertainty)	Prediction using Equation 5 (closest to field observations)
12+60	44	39	70	3.4	850 cfs	<500 cfs	1,770 cfs
16+33	31	76	130	5.6	<500 cfs	710 cfs	<500 cfs
16+33	31	76	130	8.3	<500 cfs	710 cfs	1,840 cfs
17+53	28.5	40	68	3.0	<500 cfs	755 cfs	<500 cfs
32+10	70–75	39	87	9.0	835 cfs	<500 cfs	5,150 cfs
32+10	75–87	15	22	8.1	N/A[a]	<500 cfs	5,700 cfs
32+62	55–61	110	176	None	N/A[b]	<500 cfs	N/A[b]
32+62	61–71	145	242	None	N/A[b]	<500 cfs	N/A[b]
32+62	42–52	39[c]	87	None	N/A[b]	<500 cfs	N/A[b]
35+37	97.5	40	77	3.0	<500 cfs	<500 cfs	900 cfs
35+67	30.5	47	83	6.9	750 cfs	<500 cfs	2,400 cfs
37+11	52	30	65	6.8	<500 cfs	<500 cfs	1,300 cfs
37+39	50	61	111	4.5	770 cfs	<500 cfs	1,450 cfs
37+39	22.5	25	54	4.1	<500 cfs	<500 cfs	900 cfs

a Obstruction height/D90 ratio outside bounds of equation prediction range
b Not associated with obstruction, so could not be computed
c Simulated spawning gravel deposit

obstruction submergence (h^*_c) (Equation 5 in Appendix D), proved the most reasonable. The poor results likely were due to several factors.

First, very few data points were available for obstructions higher than 1 m (3.2 ft), which was the most common obstruction height observed in this study (Table 8). Barta et al. (2000) estimate that as obstructions become larger, overtopping becomes less important, and turbulence and lateral flow velocities play greater roles in mobilizing particles. However, with so few data for these larger particles, the relationship in Figure 26 (as well as Equation 5 in Appendix D) is uncertain. More data on streams with a wider variety of slopes, obstruction heights, and channel widths would better substantiate this relationship.

Second, hydraulic predictions, integral to Equations 4 and 6, introduced much uncertainty. Computations of boundary shear stress are sensitive to slope, yet slopes vary considerably spatially (e.g., Cottonwood Bar versus boulder ribs) and temporally (e.g., at low flows versus high flows). The HEC-RAS model computes slope and predicted actual reach-wide slopes during high flows well, yet it was less accurate at low and moderate flows because boulder-induced local slopes play a greater role at higher flows. Additional HEC-RAS cross sections immediately upstream and downstream of modeled deposits would better define local slopes over a range of flows. For example, from the HEC-RAS model, the high flow slope at cross section XS 32+62 ranged from 0.038 to 0.042. Using Equation 6, the predicted flow threshold to mobilize the D_{50} = 110 mm was less than 500 cfs. However, using the field-measured, low-flow slope immediately upstream and downstream of the deposit (0.0142), the predicted flow threshold to mobilize the same D_{50} was 600 cfs. Even when applying very low slopes, predicted flow thresholds still were much lower than those observed in the field.

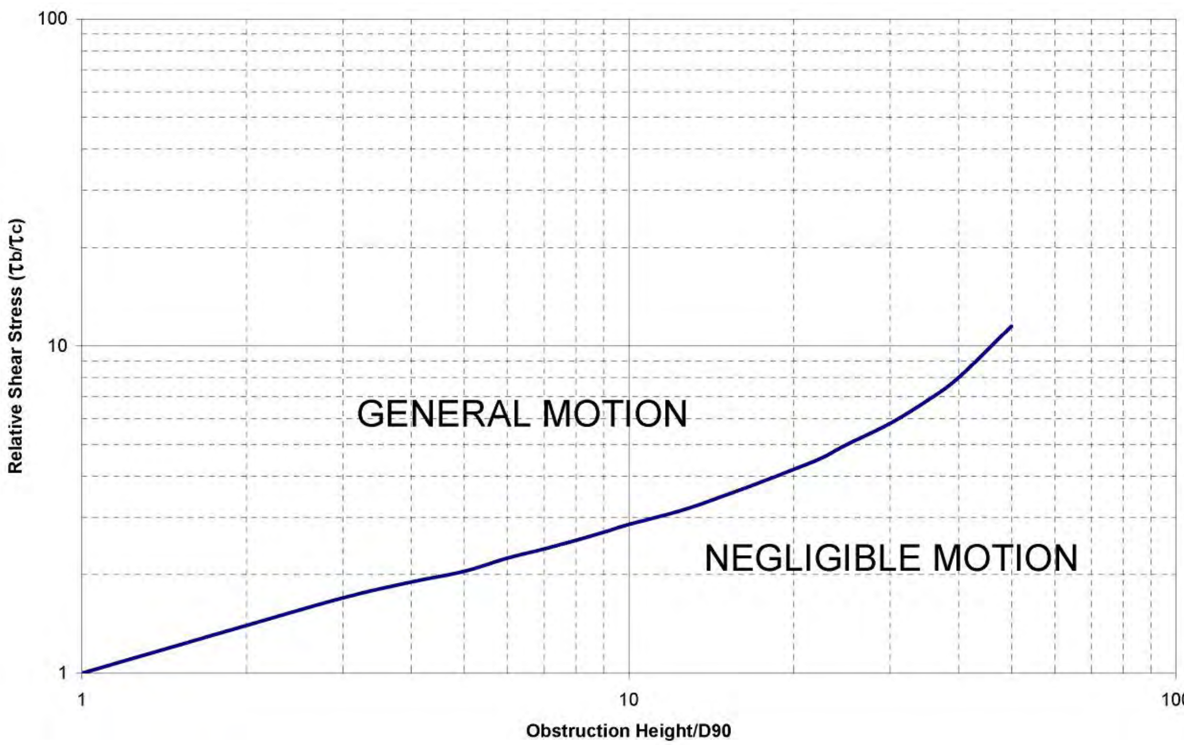


Figure 26. Relationship between relative shear stress ($\tau b/\tau c$) and obstruction height.

In summary, none of the predictions using Barta's methods earned much confidence in predicting actual bed mobility thresholds in the Clavey River mainstem, although Equation 5 tended to predict values closer to those observed in the field, as described below. Additional data collection, including lateral position of deposits within the cross section to incorporate a correction term for lateral energy diffusion, may improve these predictions. In the absence of predictive improvements, the field observations and photographic comparisons described below better estimated bed mobility thresholds of mainstem depositional features.

3.2.3. Observed Bed Mobility of Depositional Features in the Clavey River WY2005

For WY2005, the annual instantaneous maximum peak flow on the Clavey River at the 1N01 gage was 6837 cfs on May 16, 2005 (a 4.4-yr recurrence on the annual instantaneous maximum flood frequency curve, Figure 21). A peak daily average snowmelt streamflow of 4395 cfs occurred the same day (17-yr recurrence on the snowmelt flood frequency curve, Figure 16). Within the Clavey River study site, field observations of WY2005 bed mobilization are listed from largest particles to finest particles:

- No boulder movement was apparent within the low flow channel or above the low flow channel (the "low flow" or baseflow channel has the capacity to contain most flows in the gradual or slow snowmelt recession limb and all the summer baseflows).
- No cobble movement occurred in depositional features above the low flow channel.
- At 1110 cfs, small rocks could be heard impacting boulders in chutes through boulder ribs. Occasionally, these impacts sounded as if they were made by small cobbles, but this was not confirmed (even after throwing cobbles into the flow and listening for their impact).
- In run tail, pool tail, and a few lee deposits, pea gravel up to large gravel (including gravel in some rainbow trout spawning habitats) was mobilized within the low flow channel (e.g., right bank bar feature on XS 32+10).
- Large gravel was not deposited in significant amounts outside the low flow channel;
- Coarse sand was mobilized along the flank of point bars.
- In eddy deposits of pool backwaters, fine and coarse sand was scoured and re-deposited.
- Coarse sand up to 0.8 ft deep was deposited along the point bar/floodplain transition of Cottonwood Bar.

WY1992 and WY1993 Clavey River Tracer Rock Mobilization Study

In summer 1991, three sets of tracer rocks were painted in-situ in lee and obstruction deposits; the boulders were located at the forced right-bank point bar 0.3 mi downstream of the 1N01 bridge and approximately 7.5 mi downstream of the project study site (IRE 1994). The tracer rocks were painted in deposits one foot to two feet above the low flow water surface. WY1992 was a drought year, with a low peak flow. The WY1993 peak occurred on

March 17 and had a daily average streamflow of 2000 cfs. Using the frequency curve for the snowmelt maximum daily average streamflow, the WY1993 peak daily average streamflow of 2000 cfs was a 4.4-yr event. Although the tracer rocks were inundated by the WY1993 peak, they were not mobilized, as was anticipated considering that entire tracer rock sets do not mobilize in concert just as a threshold flow is exceeded. Rather, a few rocks move at lower (sub-threshold) flows, before significant movement (> 50% or >80%) occurs at a threshold streamflow. For a low gradient segment with a large-scale point bar and floodplain, mobilization of cobble lee and obstruction deposits required more than a 2.0-yr annual maximum flood or 4.4-yr snowmelt peak flood, in the middle mainstem Clavey River.

WY2005 Cherry Creek Tracer Rock Mobilization Study

D_{84} and D_{50} tracer rocks were installed March 22, 2005, on Cherry Creek cross sections XS 02+73 and XS 04+44. Pebble counts in March 2005 documented D_{84} = 100 millimeters (mm) and D_{50} = 62 mm for XS 02+73, and D_{84} = 89 mm and D_{50} = 52 mm for XS 04+44. Shortly after placement, a peak flow release of 3390 cfs from Cherry Lake Dam mobilized many of the tracer rocks (Table 9).

Table 9. Cherry Creek tracer rock mobilization results for WY2005 peak flow (3390 cfs).

Cross section	# of tracer rock sets	D_{31} (mm)	D_{50} (mm)	D_{84} (mm)	%D_{31} moved	%D_{50} moved	%D_{84} moved
02+73	13	44	62	100	100%	100%	85
04+44	15	37	52	89	100%	100%	33

When compared to observations of the WY2005 flood on the Clavey River, bed mobilization on the Cherry Creek bar was much more substantial than on the Clavey River Cottonwood Bar. On Cherry Creek Bar, which is primarily comprised of cobbles and had a water surface slope of approximately 0.0045 during the WY2005 peak flow of 3390 cfs, 100% of the D_{50} particles were mobilized. In contrast, on the Clavey River near cross section XS 16+33 with slope from 0.017 to 0.0234 (at least 3.5 times steeper than Cherry Creek) particles were not mobilized by a flow of approximately 4400 cfs. Despite the steeper slope, the large boulders that form the framework of Cottonwood Bar are large enough to shield any cobble-sized lee deposits that could potentially be mobilized.

3.2.4. Estimated Bed Mobility Thresholds from Clavey River Photographs

Sequences of photographs, taken at the same location over time, were used to verify predicted thresholds, if the flood history is known between each photographed time period. Using an assortment of ground photographs from WY1993, WY2000, WY2002, and WY2005 (and occasionally 1988 aerial photographs), bed mobility thresholds were bracketed by simply noting before-and-after photographs. In these photo interpretations, all references to annual flood recurrences were taken from the Clavey River historical flood timeline (Figure

23). The following photographic analyses are examples of how mobility thresholds of depositional features were bracketed.

Single Large Boulder Recruitment and Mobilization by a 75-yr Flood

The large boulder in Figure 27 was deposited by the January 1997 flood. The WY1988 aerial photograph shows no large boulder at Station 35+90. Judging by its sharp faces, recently chipped edges, and overall unweathered surface, it may have originated recently from the steep bedrock valley walls just upstream, rather than having been a long-time resident of the channelbed. No lee deposit has formed behind this boulder since WY1997 even though it presents a formidable obstruction to moving coarse bed material. The largest flood peak since January 1997 was a 6.3-yr annual maximum flood that occurred in WY1998, indicating no likely significant coarse bedload transport at this site. Deposition of this large boulder may be the start of a new boulder rib given the orientation of other large boulders nearby.

Coarse Sand Deposition on Cottonwood Bar's Floodplain by a 4.4-yr Flood

The narrow transition zone (looking upstream) between the point bar and aggraded floodplain—the true floodplain—is inundated frequently (Figure 28). The 4.4-yr flood peak in WY2005 deposited over one foot of sand along this transition zone in many locations.

Small Boulder Point Bar Formation by a 75-yr Flood

The 1N04 Bridge, looking upstream, is visible at the top of both photos in Figure 29. The upstream end of the project study site begins one channel bend downstream, that is, this photo pair is just outside the study reach. Wes Smith, with outstretched arms, provides scale for the size of boulders moved in the WY2000 photo. In WY1993, a lower gradient run is in the foreground of these photos; it was transformed into a shallow pool and extended tail in the WY2000 photo. The steep and straight channel approach from the bridge makes the area in the foreground of these photos an extremely dynamic target for bed mobilization. However, because the site was outside the study reach, it was not photographed in WY2005. This nucleus of a point bar should encourage deposition of finer bed material, which can be verified in WY2006. Since the January 1997 flood, the largest floods were a 6.3-yr flood in WY1998, followed by two 4.4-yr floods. These floods likely transported gravel and sand, and some cobbles (from the steep channel each immediately upstream), which should be enough to create a substrate that would promote dusky willow initiation.

Limited General Bed Mobility in a Steep and Narrow Bedrock Reach by Two 4.4-yr Floods

Looking immediately downstream from the 1N04 Bridge (above the Clavey River study site), numerous deposits have been formed among the closely spaced bedrock ribs (Figure 30). The deposit just downstream of point "E" is an obstruction deposit, the deposit behind "B" could be considered a lee deposit, and gravel in the thalweg of the photograph's foreground is a run tail deposit. Surprisingly, minor mobilization has occurred. Though large cobbles and small boulders were not mobilized by the 4.4-yr floods, finer gravel in the run tail was removed. A small sandy lee deposit on the left bank also has been scoured away. Woody riparian vegetation within the active channel continued to grow and did not appear suppressed by the WY2001 through WY2005 flows.

Figure 27. A single large boulder recruited and mobilized by the January 1997 75-yr flood at Station 35+90 within the Clavey River study site.

Figure 28. Coarse sand deposition on the Clavey River's Cottonwood Bar floodplain by a 4.4-yr flood.

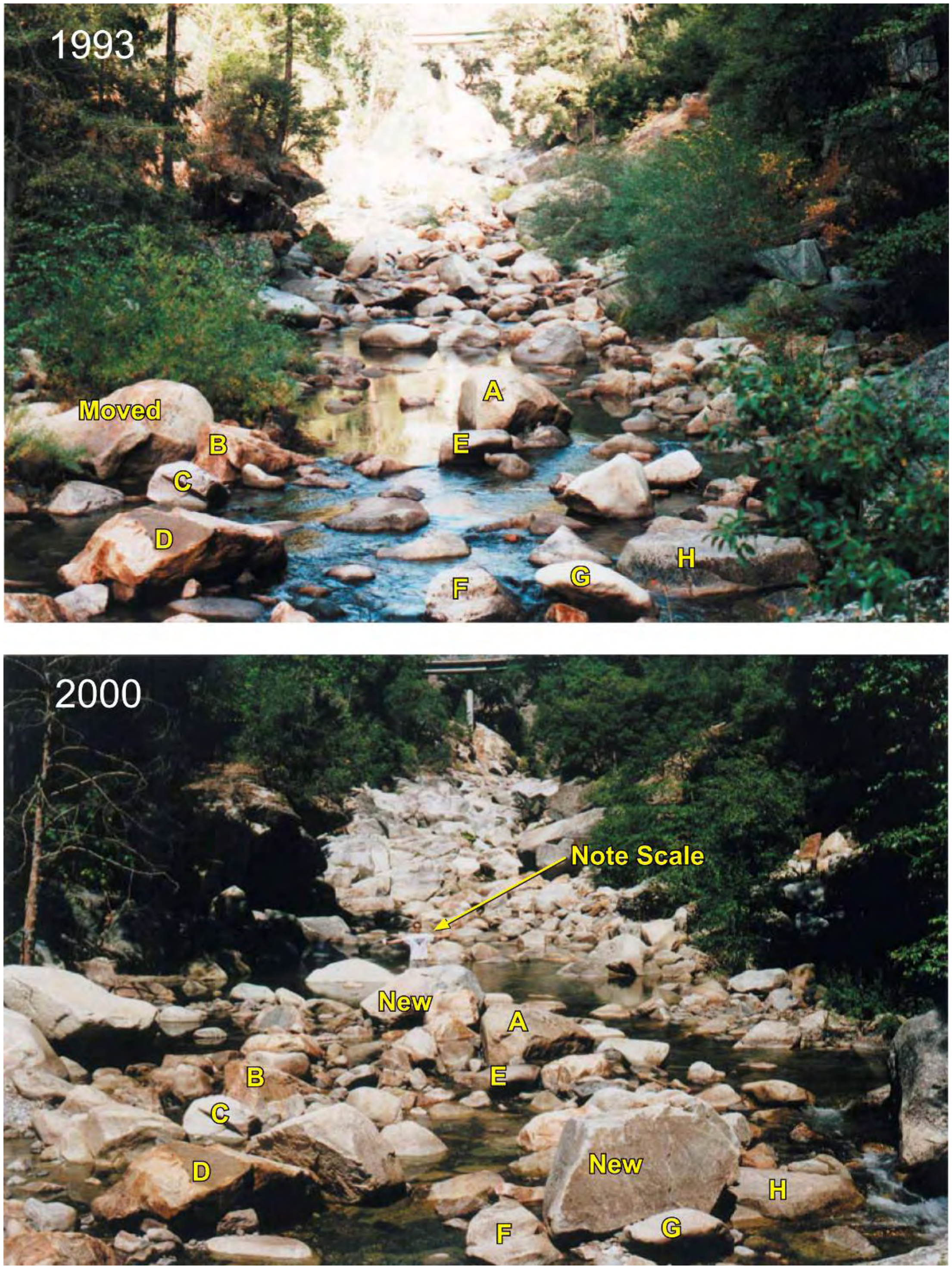


Figure 29. Small boulder point bar formed by a 75-yr flood from 1993 to 2000, photos taken downstream of the 1N04 bridge and just upstream of the Clavey River study site boundary.

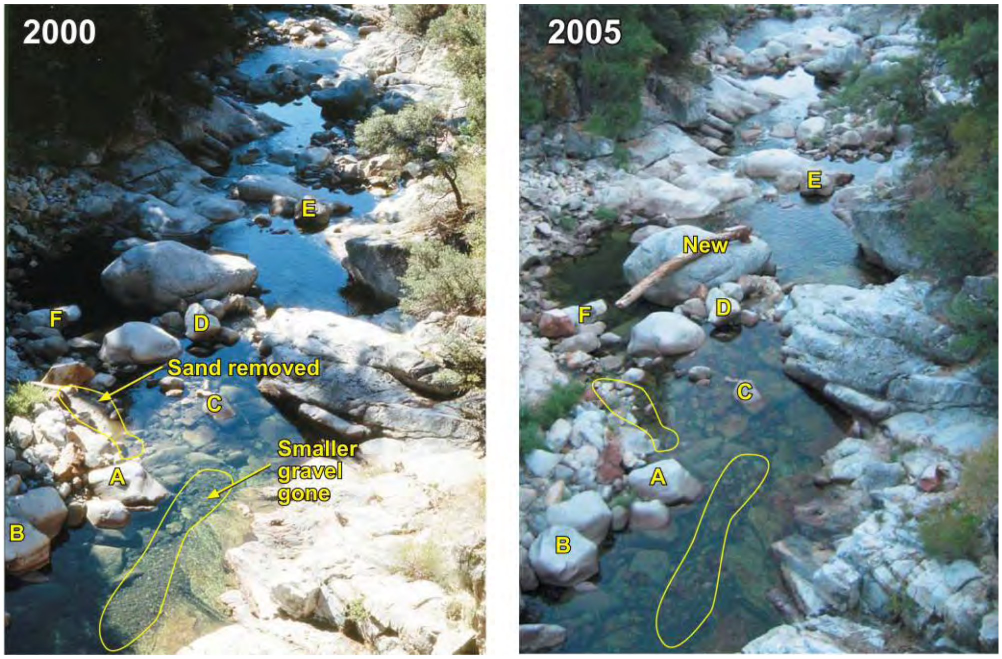


Figure 30. General bed mobility limited by two 4.4-yr floods from 2000 to 2005. The photos were taken in a steep, narrow bedrock reach of the Clavey River looking immediately downstream of the 1N04 bridge.

Large Gravel and Small Cobble Obstruction Bar Removed by a 75-yr Flood

The WY1993 photograph was taken considerably farther back than was the WY2000 photograph, as noted by the tree in both photographs (Figure 31). None of the woody vegetation within the WY1993 active channel survived, including the 8- to 10-year-old alders along the upper right of the WY1993 photograph. The matrix of coarse gravel and cobbles was mostly scoured away by the January 1997 flood; notable aggradation is not apparent up to WY2000. After the January 1997 flood, the largest flood was in WY1998, a 6.3-yr flood. The aggraded and encroached state in the foreground of the WY1993 photograph suggests minor bed mobility. Using the flood timeline, annual maximum floods barely exceeded 2-yr events from WY1987 up through WY1993, which may explain the apparent limited mobility. How the gravel and cobble was deposited initially cannot be fully explained, but the WY1986 flood was a 12-yr event and is likely responsible for the gravel and cobble deposition.

Gravel Lee Deposit Mobility and Limited Cobble Point Bar Mobility in a Narrow Steep Channel Reach by Two 4.4-yr Floods

The viewpoint in Figure 32 is looking upstream while standing on the 1N04 Bridge. Two 4.4-yr floods occurred between WY2000 and WY2005. Even though this channel segment of the Clavey River mainstem is confined, narrow, and steep, there are only very minor changes in the right bank point bar; the small boulders and large cobbles did not move. Higher up on the point bar, the bed surface becomes finer. Although photograph quality does not allow an easy determination of whether large gravel moved, the same fist-sized cobbles can be seen in both photographs. Dusky willows do not appear to have encroached the point bar over the 5-yr period, although shadows in the WY2000 photograph make assessment difficult. The WY2000 gravel lee deposit in the lower left corner appears to have been scoured away by WY2005.

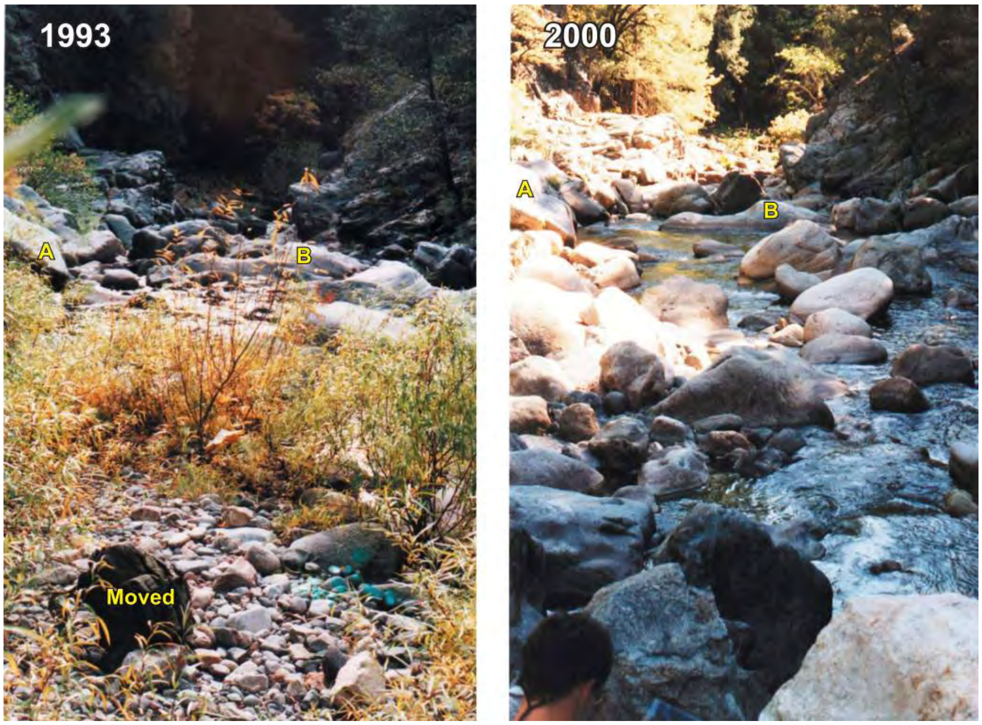


Figure 31. Large gravel and small cobble obstruction bars removed by a 75-yr flood from 1993 to 2000. The photos were taken upstream of the Clavey River's Cottonwood Creek confluence, looking downstream.

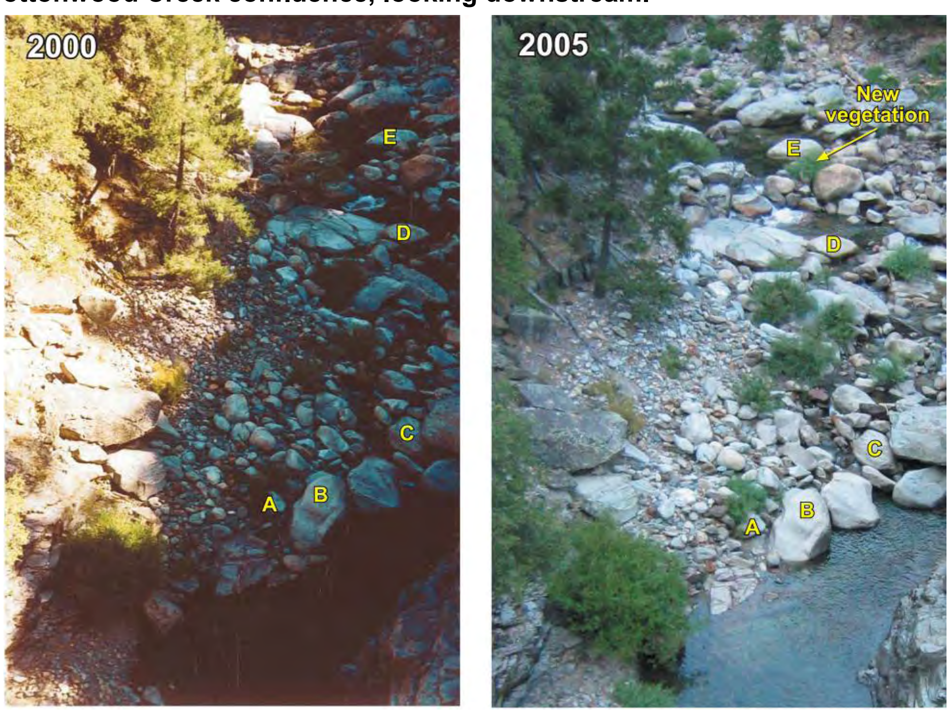


Figure 32. Gravel lee deposit and point bar mobility by two 4.4-yr floods from 2000 to 2005. The photos were taken in the Clavey River boulder sub-reach.

Small Boulder Ribs Mobilized and Reshaped by a 75-yr Flood

The portion of the boulder-bedrock sub-reach (Figure 33) looking downstream and approximately midway between the Cottonwood Creek confluence and Cottonwood Bar is slightly wider and less steep than above the Cottonwood Creek confluence. Several four- to five-foot boulders were mobilized and redistributed among the boulder ribs between WY1993 and WY2000. No prominent depositional features are evident in the WY1993 photograph, even though the WY1986 flood was able to transport significant coarse bedload. Woody riparian vegetation in WY1993 occurred just below Boulder A, and farther downstream of Boulder A, but along the right bank low flow margin. No woody riparian comeback from the WY1997 flood is obvious in the WY2000 photograph, or was observed in the 2005 field trips.

Minor Mobilization of Lee and Pool Tail Deposits in a Bedrock Reach by Two 4.4-yr Floods

No differences in cobble and boulder locations are observable in the bar upstream of the 1N04 Bridge, and young willows within the active channel that are observed in the WY2000 photograph have grown by WY2005 (Figure 30). These depositional features documented in the WY2000 photograph were likely deposited sometime in WY1998 and/or WY1999 (although deposition on the declining limb of the WY1997 is also a possibility). Note the coarsening of the gravel run tail deposits in the foreground.

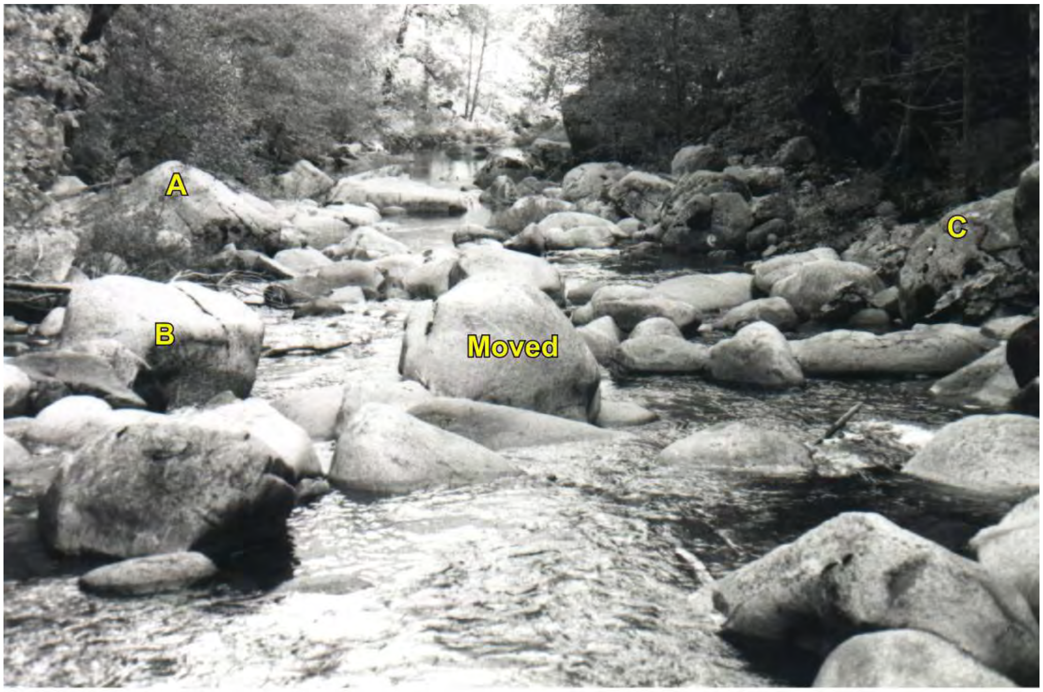
Limited Bed Mobility Below the 1N01 Bridge by a 4.4-yr Flood

A comparison of WY2002 and WY2005 photos at the 1N01 Bridge (Figure 34) documents few changes caused by two 4.5-yr floods, or by a 1.29-yr flood; no particles larger than cobbles apparently moved. Glare prevents a thorough evaluation of whether gravel deposits within the channel thalweg have been mobilized, but they were likely mobilized by high flows in 2003 and 2005. Note gravel accumulation of sand and gravel on downstream left bank point bar. Fine Sand Eddy Deposit Remaining Immobile for More than One Year on Cherry Creek in 1993

After a few years of very low annual streamflows, a 3-yr old willow (with John Bair for scale) has survived on a fine sand/silt eddy deposit in Cherry Creek (Figure 35). This depositional feature is highly mobile, and not likely to support vegetation unless flows are regulated.

Cobble Obstruction Bar Removed by 75-yr Flood

In 1993, this cobble obstruction bar near XS 12+60 was occupied by dusky willow (Figure 36). The January 1997 flood completely removed this deposit.



1993

2000

Figure 33. Small boulder ribs mobilized and reshaped by a 75-yr flood from 1993 to 2000. The photos were taken below the Clavey River's confluence with Cottonwood Creek.

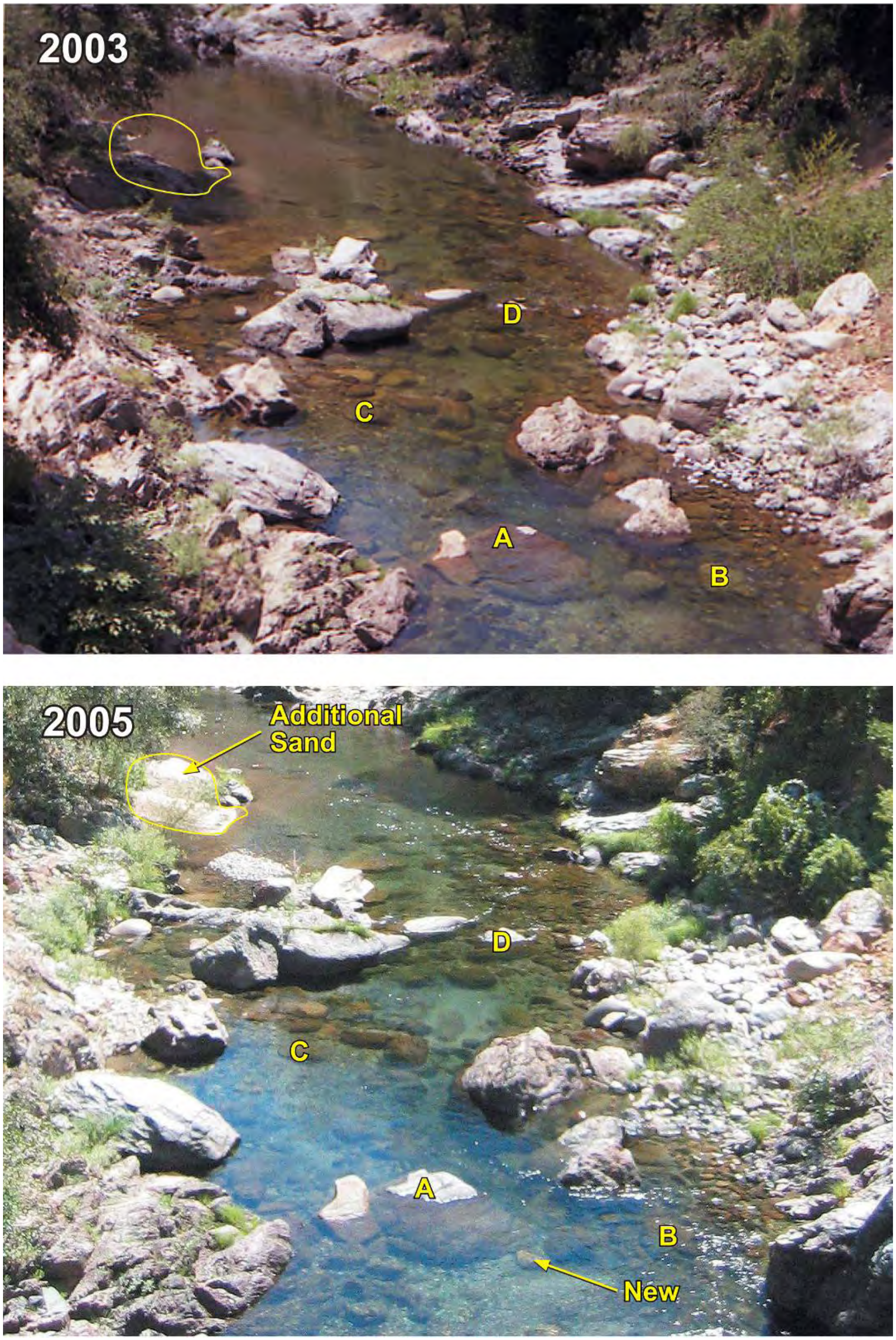


Figure 34. Bed mobility limited by a single 4.4-yr flood from 2003 to 2005. The photos were taken below the Clavey River's 1N01 bridge.

Figure 35. A three-year-old sapling established on a fine sand eddy deposit in 1993, Cherry Creek.

Sand/Gravel Deposition at Head of Lee Deposit by 6.3-yr Flood

The 1988 aerial photograph shows no lee deposit, but a lee deposit is apparent on cross section XS 35+67 in 2005 (Figure 37). In WY1998, after the 75-yr flood, a 6.3-yr flood was followed by two years with flows that did not exceed 2.5-yr flood peaks. By WY2000, sand and gravel deposition was underway. Given the minor deposition attributed to WY2005's 4.4-yr flood, the WY1998 peak was likely the key depositional event, rather than the two subsequent smaller annual peaks. By 2005, the lower region was composed of coarse gravel and cobbles, but whether these cobbles were initially deposited by the WY1998 flood is unknown. The dusky willows in the lower bar region are no older than 5 to 6 years, and exhibit signs of being partially buried during their growth, indicating active cobble deposition after the WY1997 flood.

On cross section XS 35+67, once deposition in the lee deposit got underway by WY2000 (and presumably by WY1998), woody riparian vegetation initiated and began establishing. The lee deposit has grown since 2000. A 4.4-yr flood would be several feet deep midway over this lee deposit's surface. With greater roughness induced by the vegetation, the WY2003 4.4-yr flood likely aggraded sand and gravel, and possibly some cobble at the distal end of the lee deposit. The second 4.4-yr flood in WY2005 may have induced only minor additional sand/gravel, as observed during the 2005 field survey following the flood.

The results of the January 1997 flood event can be considered when managing the release of snowmelt pulse flows. The WY1997 flood's scale is exceedingly unlikely to be attained during a snowmelt runoff period during the contemporary climatic regime. Large rain-on-snow events nearly always occur as winter floods, not as spring snowmelt. WY2005 was an

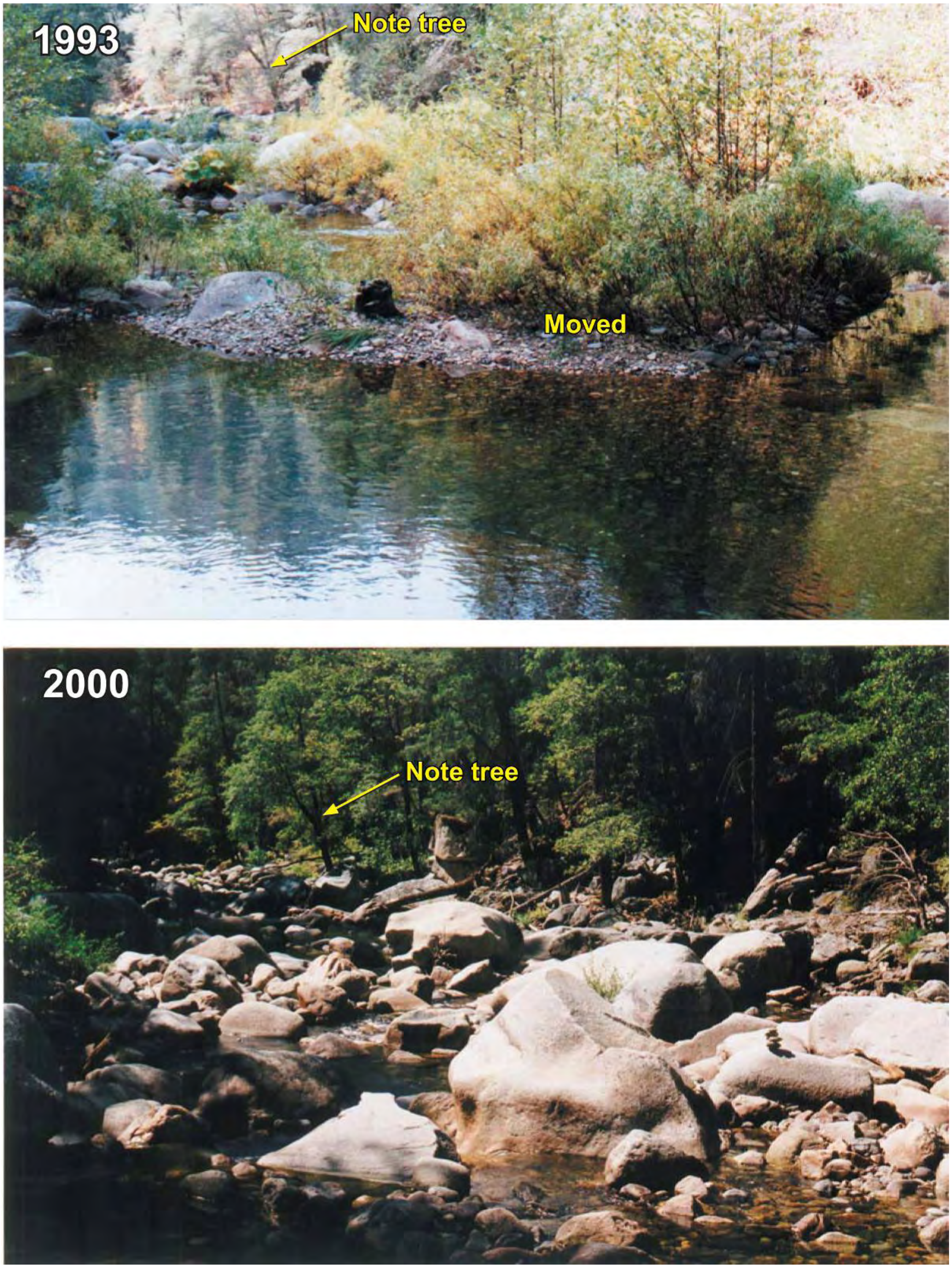


Figure 36. Cobble obstruction bar scoured by a 75-yr flood from 1993 to 2000.

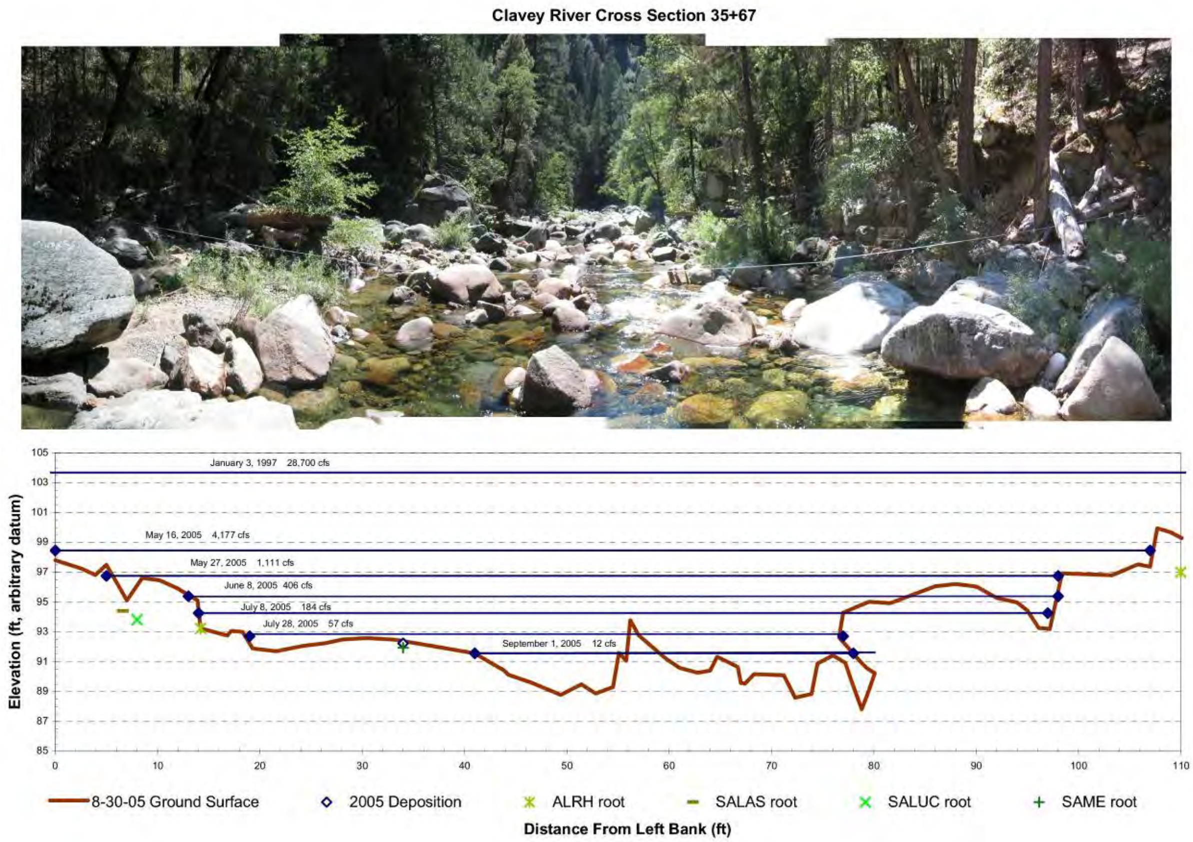


Figure 37. Sand/gravel likely deposited (lee deposit) by 6.3-yr flood in 1998, photo taken 2005 at Clavey River cross section 35+67.

exception, when an unusually large rainfall event occurred during the spring snowmelt runoff period. While this event created a large magnitude flood, as measured at the 1N01 Bridge (6,837 cfs), it was nevertheless much smaller than the WY1997 flood (47,000 cfs), and accordingly had much less geomorphic impact.

Photographic comparisons showed that the 75-yr WY1997 flood performed the following geomorphic functions: (1) in the active channel, many large boulders up to six feet in diameter were mobilized, but those larger than a six-foot diameter were not mobilized, (2) in the active channel, some boulder riffles were completely removed, (3) large boulder blocks from the valley's bedrock sides were recruited to the mainstem channel, to serve as future boulder rib members, and (4) most willows within the active channel in small depositional features were scoured away, yet willows in large boulder fields were often sheared off at the root crown, and they were able to re-sprout in the following years.

3.2.5. Summary: Bed Mobility Thresholds

From comparisons of bed mobility modeling, field observations, and examination of paired photographs, flow thresholds for mobilizing depositional features were attributed to annual maximum flood recurrences (Table 10). This table and its discussion largely fulfill Objective 1 (Section 1.2).

Table 10. Recurrence and magnitude thresholds for depositional and scour processes, as estimated from hydrologic data collected at USGS Gage No. 1283500, at the 1N01 bridge, Clavey River near Buck Meadows.

Annual maximum flood recurrence (yrs)	Annual maximum flood peak magnitude (cfs)	Mobilization actions accomplished
1.5 to 3	1,300 to 3,700	Mobilize surfaces (occasionally deeper) of gravel deposits close to the thalweg of pool/run tails and between boulders in boulder ribs not on the thalweg. Deposit/scour/reshape silt and sand eddy deposits. Mobilize coarse sand stored in pools. Likely exchange coarse sand in the matrix between cobbles and small boulders of larger depositional features within the low flow channel and along the flanks (forming one bank of low flow channel) of larger depositional features (e.g., point bars).
4 to 6	6,500 to 10,000	Deposit sand/gravel onto many smaller depositional features (e.g., lee deposits) in the low flow channel. Deposit coarse sand and small gravel onto point bar/floodplain transition areas. Induce minor gravel scour/re-deposition in pool/run tails and leading edges of large point bars. Maintain side channels by scouring away sand and gravel. Selectively mobilize some cobbles in coarser features close to the thalweg.
12 to 17	18,000 to 23,000	Mobilize/shape/reshape gravel and cobble depositional features in the low flow channel (e.g., lee and obstruction depositional features). Deposit sand/gravel onto large point bars and floodplain transition areas. Significantly/entirely remove prominent gravel/small cobble pool tail deposits. Scour behind boulder ribs previously buried by bigger floods. Deposit coarse sand onto floodplains and fine sand/silts onto higher depositional features (e.g., aggraded floodplains). Moderately reshape existing side channels. Pack small boulders/large cobbles against larger boulder ribs. Create larger woody debris jams capable of influencing local hydraulics of smaller snowmelt floods.

Table 10 (continued)

Annual maximum flood recurrence (yrs)	Annual maximum flood peak magnitud e (cfs)	Mobilization actions accomplished
70 to 100	45,000 to 55,000	Aggrade large point bars and lateral bars with boulders and large cobbles (e.g., as in the upper half of Cottonwood Bar). Form/reshape/eliminate smaller boulder ribs. Scour/construct small point bars. Create/remove side channels. Deposit sand onto old aggraded floodplains and terraces. Transport very large boulders that calved from nearby steep bedrock valley walls short distances.

A gap in flood recurrences and magnitudes is prominent in these geomorphic thresholds; it is the 30-yr to 45-yr annual maximum recurrences with peak magnitudes of approximately 32,000 cfs and 40,000 cfs at the 1N01 gage. The 12-yr to 15-yr flood events followed by a 75-yr flood effectively removed woody vegetation within the active channel, leaving few clues of what a 30-yr to 45-yr flood might accomplish geomorphically. According to the flood timeline (Figure 23), no 30-yr to 45-yr flood events have occurred since WY1960. During the higher end of 12-yr to 15-yr floods but less than approximately 25-yr floods, many secondary hydraulic controls should be significantly drowned out (i.e., many of the larger boulder ribs would be inundated by flood waters). This may represent a larger scale threshold, where floods between 25-yr and 70-yr floods (and larger) may not accomplish dramatically different geomorphic feats, but only gradually accomplish more.

Another gap in flood recurrences and magnitudes occurs in the 8-yr to 10-yr annual maximum recurrences. From a management perspective, this gap in geomorphic thresholds is more problematic. Floods of 8-yr to 10-yr annual maximum recurrences with peak magnitudes of 13,000 cfs to 16,000 cfs may be at or just approaching the threshold for accomplishing what 12-yr to 15-yr floods readily accomplish. The operational challenge of releasing a 20,000 cfs event rather than a 13,000 cfs event would be considerably easier.

Another geomorphic threshold may occur at 150-yr floods or greater, where primary hydraulic controls become important (e.g., backwaters created by valley wall constrictions, with huge downstream standing waves). However, reservoir operators would rarely have cause to release a 150-yr flood event, so this threshold is not evaluated further.

For the practical mission of identifying flow thresholds to recommend pulse flows, the above thresholds indicate that winter floods (almost all 4-yr flood recurrences and greater) are responsible for most of the "heavy" geomorphic work. Snowmelt floods, while not as dramatic as winter floods, are responsible for "lighter" geomorphic work, but are of extreme importance to woody riparian vegetation initiation and establishment. In turn, riparian vegetation establishment can greatly affect the mobility of many depositional features.

3.3. Ecological Analyses

3.3.1. Willow Seedling Initiation and Establishment

On a depositional feature such as Cottonwood Bar, the first hurdle in establishing woody riparian vegetation is plant initiation, which is seed germination followed by seedling survival through the first growing season. Initiation requires sufficiently moist germination sites during the seed release period (primarily in spring) and sufficiently slow snowmelt recession flows, such that seedling roots can "keep up" with decreasing soil moisture (McBride et al. 1988; Mahoney and Rood 1992; Segelquist et al. 1993; Mahoney and Rood 1998; Amlin and Rood 2002). As flows recede during the snowmelt recession period, the retreating shallow groundwater table and its capillary zone become less accessible to seedlings. A seedling will survive its first summer and early-fall only if its root growth tracks with the decrease in groundwater elevation.

Following initiation, the next hurdle is establishment: survival to sexual maturity. If a seedling has managed to survive to early-fall (having survived deer grazing as well as desiccation), the next challenge is to survive scour by winter floods. The higher magnitude but less-frequent floods occur in winter, so the type of water year following initiation (wet or dry, and mild or intense) is important. Following winter floods, the annual spring snowmelt peak can also scour seedlings (especially if the winter had been mild); seedlings can also be sand-blasted through long exposure to coarse sand as it is transported near the bed surface. Following the spring snowmelt peak, a seedling again risks desiccation (and browse) during its exposure to a second snowmelt recession limb and summer baseflows.

Desiccation risk could be high if flows in the second spring and summer are much lower than those of the first spring and summer. An "adult" willow typically requires approximately 10 years to become sexually mature, so a willow seedling must survive approximately ten annual iterations of desiccation and scour (and browse and disease) to become established.

The last hurdle is persistence, which is growth and reproduction for as many years as possible. As alders and some willow species age, they gradually become more rigid, and therefore they are less likely to bend and more likely to crack or break-off during bigger floods. Other willow species are more shrub-like than tree; for these shrubby willows, a large flood can strip many or all the branches, but the willow can still vigorously re-sprout. The price for persistence can be loss of reproductive vigor, but producing fewer or less viable seeds in some years is better than prematurely becoming large woody debris.

3.3.2. Woody Riparian Field Observation and Photograph Assessment

Depositional features within river channels should be good places, if not the best places, for initiation of woody riparian seedlings. However, a field tour of the Clavey River and Cherry Creek in WY2005 indicated that the relationship between plants and depositional features in boulder-bedrock river channels is complex. Cottonwood Bar (Figure 38) is one of the largest depositional features in the mainstem Clavey River; its gently sloping point bar surface supports numerous patches of fine sand and gravel, minimizes impacts of large scouring floods, and provides ample sunlight. All these physical traits should encourage woody riparian establishment, yet on Cottonwood Bar, willows and alders are found only in selected areas, which are along the bar's margin that is close to summer baseflow stage height, and in scour pockets behind exposed boulder ribs. Elsewhere on the Clavey River mainstem, established woody riparian vegetation is sporadic, primarily in smaller depositional features such as lee and obstruction deposits. Some gravel lee deposits support dense three-year-old dusky willows, while other similar deposits will be devoid of perennial plants. Along the Clavey River mainstem, visible woody debris wedged among boulders and stranded high in trees indicates that recent flooding is a dominating factor that determines which trees live and which die.

Figure 38. Panoramic photograph of the Clavey River's Cottonwood Bar looking downstream.

In Cherry Creek, most floods have been suppressed for approximately 50 years. Surrounding the USGS stream gage on Cherry Creek (USGS Gage No. 11277300), post-1950s willows and alders support the hypothesis that in the absence of most floods, woody riparian vegetation will encroach into the mainstem channel. A large point bar called Cherry Bar (Figure 8C), similar to the Cottonwood Bar on the Clavey River, supports good patches of germination substrate, minimizes flood impacts, and provides ample sunlight. With most floods suppressed and with good substrate, dense patches of willows and alders would be expected. However, Cherry Bar is not blanketed with willows and alders either, although there are more alders on its open bar surface than on Cottonwood Bar. A possible explanation was indicated by the many lee deposits along Cherry Creek's channel margin, which have accumulated several feet of sand and fine gravel, interlaced with large post-1950s ponderosa pine and much younger alders and willows. These sand-aggraded lee deposits are missing from the WY2005 Clavey River channel. Unlike Cottonwood Bar, conifers are common on Cherry Bar.

3.3.3. Estimated Willow Scour and Removal Thresholds

Paired photographs, used to describe mobility thresholds for depositional features (Section 3.2.4), also provide insight into woody riparian processes and thresholds. One very obvious observation is that most photographed depositional features in the Clavey River, regardless of the photograph's date, supported no woody riparian vegetation or only a fringe of one foot to two feet high dusky willows. For example, a larger than usual lee deposit (Figures 39A and 39B) has ample favorable substrate for nurturing willow and white alder seedlings. In Figure 39A, the capillary fringe (indicated by the visible dark sand), reaches the bar's surface just along the streamside perimeter of the big boulder, which maintains favorable moisture conditions late into the summer. This lee deposit must have been significantly mobilized by the January 1997 flood, when peak flood stage overtopped the largest boulder in Figure 39B (on the mid- to upper-right margin of the photograph) by several feet. Given that the January 1997 flood occurred eight years before the photo was taken, reasons for the conspicuous lack of initiation and early establishment for willows and white alders are not readily apparent.

Field observations and a closer inspection of photographs (Figures 39A and 39B) provided a possible explanation for the lack of willow and white alder initiation and establishment. Dusky willows partially fringe the deposit's margin, although most are at its downstream end. After excavating around their bases (an excavated willow base is 10 ft to the right of Allison in Figure 39A), most excavated willow bases exhibited older root collars than stems. The stems were younger than WY1997, but many of the root collars appeared much older. Aging of the dusky willow roots was attempted, but results were mixed. Many of the willows observed in WY2005 had likely survived the January 1997 flood, but their branches were sheared off; their roots were protected by wrapping around smaller boulders that were protected from scour by much larger boulders.

Events since January 1997 have not favored willow and alder seedling initiation or early establishment on the larger depositional features in the mainstem Clavey River. The Clavey River flood timeline (Figure 23) demonstrates a relatively mild period after January 1997, with the largest flood in WY1998 (a 6.4-yr flood) followed by the two 4.4-yr floods. The bed mobility analysis indicates that these frequent, low-magnitude flood events may have barely mobilized some surface cobbles in the lower left of Figure 39A, but the events likely deposited sand and gravel higher on the lee deposit (where Allison is sitting). Sand and gravel deposition, however, typically occurs on the declining limb of the flood. What may appear to be minor scour during a flood's peak, may be sufficient to remove seedlings. Scour chains or scour cores need to be installed to monitor scour and deposition during a single low-magnitude flood event.

Given a willow's persistence characteristics, scour may not be the best, or only, causal explanation. In Figure 39B, dusky willows are prominent in three locations: (1) at the very downstream end of the lee deposit and toward the right bank, (2) downstream of the lee deposit and behind an intermediately sized boulder perched on smaller boulders, and (3) in the photo's right foreground, opposite the lee deposit. All three locations exhibit willows

Figure 39A. Lee deposit on the mainstem Clavey River, upstream of its confluence with Cottonwood Creek, August 30, 2005.

Figure 39B. Same lee deposit on the mainstem Clavey River, looking toward the right bank, August 30, 2005. River flows from right to left.

that are rooted very close to the base summer flow, or in the summer flow. The top of the lee deposit is a few feet above the low-flow summer stage. Although capillary forces wick up moisture into the deposit, the surface that a dusky willow seed would land on is dry, and so would not germinate. This surface dryness may not be sufficiently accounted for in modeling willow initiation's earliest stage of seed germination. Moisture is not far below, but nevertheless it is not where it is needed.

From WY1980 up through spring of WY1986, several large floods seem to have inhibited woody riparian establishment, and even initiation. The August 1988 aerial photographs for the upper Clavey River study site reveal obstruction bar features, located at the downstream end of pools formed by large boulder ribs, that have little if any woody riparian vegetation. These are features that favor woody riparian initiation and establishment. Either collectively (WY1980 17-yr flood, WY1982 12-yr flood, and WY1986 12-yr flood) or individually (WY1986 flood), the floods apparently scoured many large gravel and cobble depositional features, as seen in the 1988 aerial photographs. Note that the biggest floods before WY1980, occurring in the early 1960s, were no bigger than the early- to mid-1980 floods. If the 1980s floods did not mobilize lee and obstruction deposits, then neither would those of the early 1960 floods. Woody riparian vegetation would have had several decades to achieve prominent establishment.

On Cottonwood Bar, removal of 8-yr to 12-yr old alders by flood peaks less than 10-yr is very unlikely. Although 8-yr to 12-yr old white alders were present on Cottonwood Bar in WY1993 (Figure 40), none were present in WY2005 (Figure 38). After examining the flood timeline (Figure 23), one plausible explanation is that white alders were removed by the January 1997 flood. However, other floods between WY1993 and WY1997 may have had the capability to remove the alders. In WY1995 and WY1996, 10-yr and 11-yr floods occurred, respectively (Figure 23), so the alders on Cottonwood Bar could have been removed before January 1997. In any case, the threshold for removing the 8-yr to 12-yr old alders must be between a 10-yr flood and a 75-yr flood. With no other information, other than the pair of photographs and the flood timeline, logic dictates that the threshold could even be less than a 10-yr flood. However, after observing the effects of a 4.4-yr flood in WY2005 on saplings (no effect), channelbed mobility, and the hydraulic geometry of channel cross sections, removal of 8-yr to 12-yr old alders from Cottonwood Bar by flood peaks less than a 10-yr flood is very unlikely. Partial to complete removal could be accomplished by floods ranging from a 10-yr to a 75-yr flood, which is a wide range from a flow pulse management standpoint.

Figure 40. Presence of 8- to12-year-old white alders on the Clavey River's Cottonwood Bar in 1993.

To further refine the range of flows that could remove the 8-yr to 12-yr alders, WY1993 photographs and the flood timeline were analyzed. Peak flood magnitudes in the early 1960s (WY1963, a 17-yr flood and WY1965, a 9-yr flood) were similar to those in the early- to mid-1980s (WY1980, a 17-yr flood; WY1982, a 12-yr flood; and WY1986, a 12-yr flood) (Figure 23). These two periods contained the greatest floods, beginning with WY1960 and leading up to the January 1997 flood. Similar flood magnitudes were assumed to impose similar effects on woody riparian vegetation, so if a scour threshold for 8-yr to 12-yr-old alders was not surpassed in the 1980s, it would not be surpassed in the 1960s either. If neither period surpassed the threshold for removing 8-yr to 12-yr-old white alders, then Cottonwood Bar should have had much older, taller, and likely more, white alders present in the WY1993 photographs. Between WY1960 and WY1993, the 17-yr floods in WY1963 and in WY1980 very likely exceeded the flood threshold for eliminating the 8-yr-old to 12-yr-old white alders from Cottonwood Bar. Therefore, the search for a flood threshold range has been narrowed to a 10-yr (15,000 cfs) to a 17-yr (23,000 cfs) flood.

Other large depositional features photographed in WY1993 also had white alders up to the 8-yr to 12-yr old range (e.g., Figure 41). A 15-yr annual maximum flood magnitude of 21,000 cfs was considered the likely threshold for eliminating 8-yr to 12-yr old alders from large depositional features.

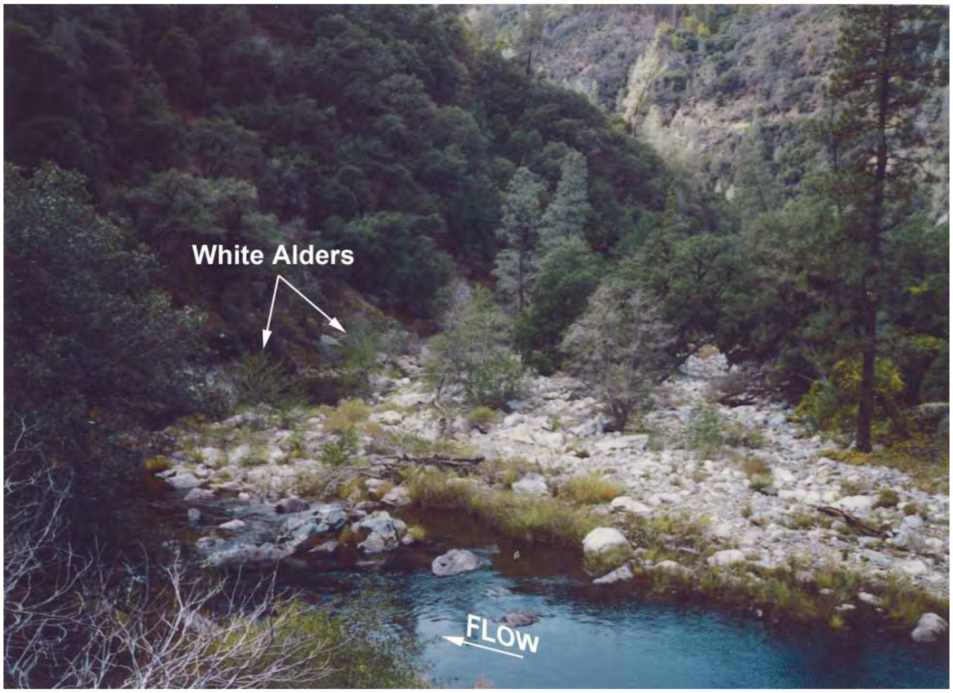


Figure 41. Presence of 8-year-old to 12-year-old white alders on a large point bar below the Clavey River's 1N01 bridge in 1993.

3.3.4. Summary: Willow and Alder Removal Thresholds

Flood thresholds observed or documented in the photographs for willows and alders are proposed for the Clavey River study site (Table 11). These thresholds attempt to impose discrete thresholds on what must be a continuum in nature. A higher flood threshold (that is, a > 15-yr to a 20-yr flood) was not proposed because mature trees (white alders 15-years-old to 20-years-old) were found to have survived the January 1997 flood by either: (1) occupying a highly sheltered floodplain or lateral bar surface, or (2) being protected by a large boulder. Many willows, particularly dusky willow, observed before the January 1997 flood were present after the flood. The 75-yr WY1997 flood may not have been sufficient to be considered a resetting threshold flood that essentially removes all plant life.

Table 11. Willow and alder removal thresholds on the Clavey River.

Age of willow or alders (yrs) and type of depositional feature	Approximate flood recurrence (yrs)
Mature trees within the baseflow channel and protected saplings on large depositional features	> 20
Older saplings (> 10 years old) from large depositional features	15 to 20
Older seedlings (3 years old) from large depositional features and possibly young saplings from the margins of large depositional features	10 to 12
Older seedlings (3 years old) from small depositional features (many of the lee deposits) within the baseflow channel	5 to 8
Young seedlings from exposed small depositional features and prevent early establishment along the fringe of large features	3 to 5
Preventing early establishment on small depositional features within the baseflow channel	1.5 to 3

3.3.5. Life Histories and Habitat Requirements

While generally predictable for an individual species over a geographic range, life history timing is influenced by numerous environmental cues and can vary among water years. Water temperature is a major factor influencing life history timing for many aquatic species. For example, water temperature can influence: (1) the timing of amphibian oviposition and trout spawning, (2) duration of egg incubation before hatching, (3) larval and juvenile growth rates and survival, and (4) benthic macroinvertebrate production. Typical life history timing and temperature thresholds for each species and life stage were compiled from available literature and are described in this section.

Rainbow Trout

Rainbow trout are typically a prominent (if not the only) species considered when instream flow recommendations are being evaluated. Though rarely explicitly stated, rainbow trout are often considered indicators of stream health, with the assumption being that flows that are good for rainbow trout must be good for Sierra Nevada river ecosystems. Though using rainbow trout as a health indicator has not been assumed in the project, rainbow trout are important members of the river community and should be considered in recommending a pulse flow strategy.

Rainbow trout are the most common and widely distributed fish in the mainstem Clavey River (Clavey River Wild and Scenic River Value Review 1997). They prefer cool, clear, fast-flowing streams and rivers where riffles dominate over pools, cover is provided by riparian vegetation or undercut banks, and the benthic macroinvertebrate prey base is diverse and abundant. Rainbow trout show distinct habitat preferences at different sizes and life history stages. Fry (< 2 inches (50 mm) standard length [SL]) typically concentrate in shallow, low-velocity water along stream edges where flow depth is < 1.6 ft and velocity is 0.03 feet per second (ft/s) to 0.5 ft/s. Juveniles (2 inches to 5 inches [50 mm to 120 mm] SL) prefer deeper, swifter water with cover provided by rocks or other submerged debris. Preferred flow depth is 1.6 ft to 3.3 ft. Suitable focal point velocity is 0.3 ft/s to 0.4 ft/s, with a maximum of 0.7 ft/s. Larger juveniles and adults seek out deeper, low-velocity habitats (such as pockets behind rocks, runs, and pools) but generally remain close to swift water that delivers benthic macroinvertebrate drift.

Cover is essential for all life history stages and can be provided by overhanging vegetation, submerged vegetation, undercut banks, pool depth, surface turbulence, and submerged objects (e.g., logs, boulders). Trout overwinter in a state of torpor when temperatures decrease to 39°F. Adults overwinter in deep pools, while juveniles burrow into interstitial spaces within coarse gravel and small cobble deposits. The California Department of Fish and Game has monitored rainbow trout abundance, size, and distribution at various locations in the Clavey River since 1984. Different sites were sampled in different years, but the highest trout abundance observed consistently occurred at the 1N04 Bridge or Twomile Creek.

Trout are sensitive to high water temperature (Table 12); summer temperature is one factor that influences the downstream distribution of trout in the mainstem Clavey River (Tuolumne County and TID 1990). Suitable temperatures for all trout life history stages range from the mid-40°F up to 70°F.

Table 12. Temperature (°F) suitability for rainbow trout life stages.

Life stage	Suitable temperature (°F)
Incubation	**45 to 54**
Fry	**55 to 66 (optimal for growth)**
Juvenile	**59 to 68 (optimal)**
Spawning	**50 to 54 (optimal)**

Sources: Moyle 2002; McCullough 1999; Raleigh et al. 1984.

Life history phenology (or timing) for rainbow trout in the Clavey River is closely tuned into the snowmelt hydrograph from April through early July (Figure 42). Rainbow trout spawn in coarse gravel deposits of pool and run tails, or in gravel lee deposits between boulder ribs. During spawning, the female excavates a redd, deposits her eggs which are fertilized externally by the male, then buries the fertilized eggs. Optimal substrate size for spawning depends on spawner size. For trout smaller than 20 inches (typical for the Clavey River), optimal substrate consists of a mixture of gravel ranging from 0.6 inches to 2.4 inches in diameter. Suitable flow velocity at spawning sites is 1 ft/s to 2.3 ft/s; suitable flow depth is 0.3 ft to 4.9 ft. Eggs incubate in the gravel for three to four weeks (at 50°F to 59°F). Larvae (called *alevins*) remain in the gravel for two to three weeks, emerging 30 to 50 days (or more) after fertilization depending on water temperature. During spawning surveys in the late-1980s, spawning was observed in a tributary (Twomile Creek) in April (Tuolumne County and TID 1990). Fry were observed from June 8 through August 7 the same year.

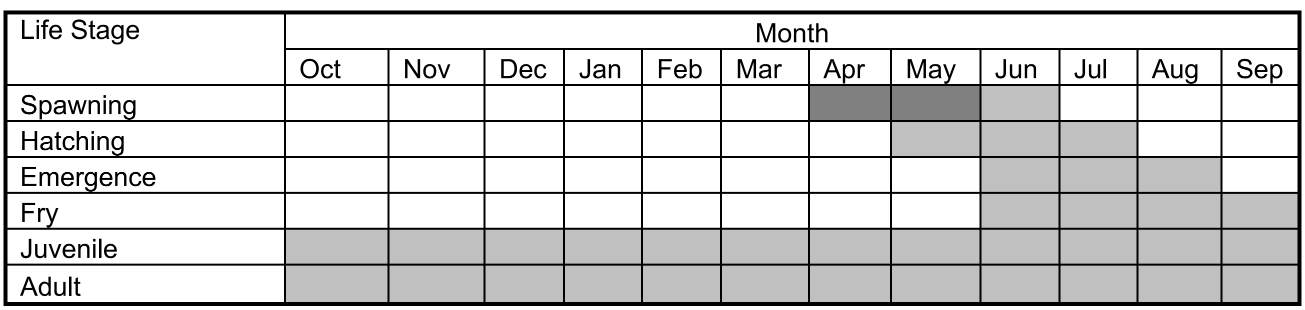


Figure 42. Rainbow trout life history phenology. Shaded boxes indicate activity periods, darker shading suggests peaks in activity.

Foothill Yellow-Legged Frog

Foothill yellow-legged frogs (*Rana boylii*) are found in most Pacific drainages from the Santiam River in southern Oregon to the San Gabriel River in southern California. In the Sierra Nevada, they occur west of the Sierra Nevada-Cascade crest up to 6400 ft elevation (Jennings and Hayes 1994). This species, eliminated now from 66% of its former range, has suffered significant population declines and currently is a California Species of Special Concern and a candidate for Federal listing (Jennings and Hayes 1994).

Foothill yellow-legged frogs are highly aquatic, spending most or all their life cycle close to perennial streams or intermittent streams that retain pools. Streams with gradients less than 4% are preferred, but they have been observed in steeper streams (Seltenrich and Pool 2002). Adults often live in high-gradient streams, though oviposition may be limited to lower gradients (Amy Lind, personal communication 2006). Several environmental cues, including water temperature, air temperature, day length, and streamflow influence breeding timing in foothill yellow-legged frogs and other amphibian species (Lind 2004). Breeding begins after high winter floods and during the snowmelt hydrograph with egg laying in late-March through early June (Jennings and Hayes 1994). On the Trinity River (Northern California), egg laying begins May and extends through early June, depending on the hydrograph (Ashton et al. 1997). At any one locality or year, breeding usually occurs within a period of two to three weeks. Eggs are deposited in clusters attached to the sides or undersides of cobbles and boulders. Although cobbles and boulders are preferred, vegetation, woody debris, and gravel are also used. Oviposition sites are typically in sunny areas, often on point bars, lateral bars, side channels, pool tailouts, side-pools, and along the main channel margin. Water depth at oviposition sites is 1.5 to 16 in (Lind 2004); flow velocity ranges from 0 ft/s to 0.7 ft/s (Lind 2004). Eggs hatch in 5 to 30 days, depending on water temperature, with shorter incubation at higher temperatures. Eggs have been observed in water temperatures from 48.2°F to 69.8°F; the critical thermal maximum for eggs is 78.8°F (Zweifel 1955, as cited in Lind 2004). For several days after hatching, tadpoles are poor swimmers and thus remain near the oviposition site, dispersing as they grow.

A minimum of 15 weeks after oviposition is required to reach metamorphosis, which typically occurs between July and September (Jennings and Hayes 1994). Throughout rearing, tadpoles prefer warmer edgewaters along the mainstem channel. The maximum observed water temperature reported for tadpoles is 86.4°F (Zweifel 1955, as cited in Lind 2004). Juveniles and adults remain strongly associated with cobble bars and slow moving water. Early life history phenology for foothill yellow-legged frogs almost directly overlaps the timing of the snowmelt hydrograph (Figure 43).

Life Stage / Activity	Month											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Courtship												
Breeding												
Egg development												
Larvae (tadpoles)												
Sub-adults (metamorphosis)												
Overwintering												

Prepared by D. Ashton

Figure 43. Foothill yellow-legged frog life history phenology. Shaded boxes indicate activity periods; darker shading suggests activity peaks.

Western Toad

The western toad (*Bufo boreas)* is found throughout much of the western United States and Canada. In California, this species ranges statewide to an elevation of 10,000 ft, except in deserts (CDFG 1988). The terrestrial adults are can be found in prairies, forests, canyon grasslands, and pine-oak forests. In drier climates, adults stay near water bodies.

In California, the western toad's breeding period extends from January through July, but in snowmelt systems the breeding period may begin later, approximately April (Figure 44), depending on local temperature and snowmelt conditions (CDFG 1988). Breeding begins as average water temperature reaches 32°F (Salt 1979), but breeding can also occur at snowmelt, even with ice still on water surfaces (Don Ashton, personal communication 2006). At higher elevations, the onset of breeding was assumed to be April or May in the project study sites. Eggs are laid in permanent waters, including wetlands, ponds, lakes, reservoir coves, and stillwater off-channel river habitats (i.e., any body of water without a strong current). Water depth at oviposition sites is typically 2 to 20 inches (CDFG 1988). Eggs are laid in long strings on bare sediment or intertwined in vegetation in shallow water near shore. Embryos develop rapidly, and eggs hatch in 3 to 10 days depending on water temperature (Leonard et al. 1993). Tadpoles metamorphose two to three months after eggs are laid, depending on temperature and food availability (Olson 1996). After metamorphosis, toadlets disperse en masse from breeding sites.

Life Stage	Month											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Breeding												
Egg development												
Larvae (tadpoles)												
Subadult												
Adult												
Overwintering												

Prepared by D. Ashton

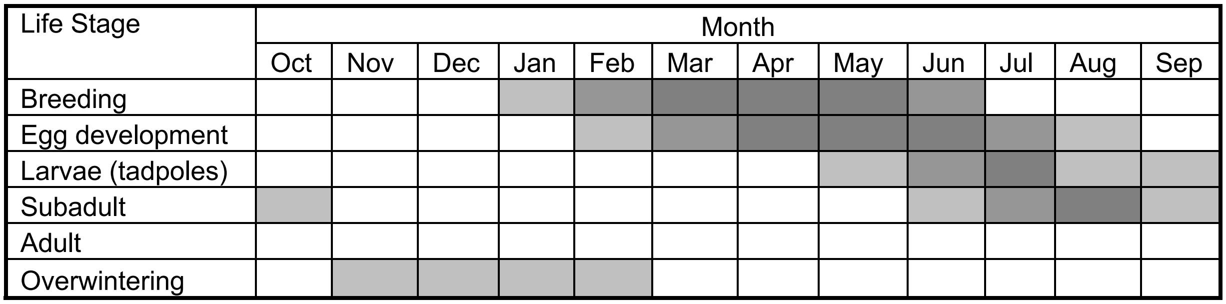
Figure 44. Western toad life history phenology. The shaded boxes indicate activity periods; darker shading suggests activity peaks.

Pacific Treefrog

Pacific treefrogs (*Pseudacris* [*Hyla*] *regilla*) are found from British Columbia to the southern tip of the Baja peninsula. In California, this species occurs throughout the state from sea level up to an elevation of 11,000 ft (CDFG 1988). The ground-dwelling adults live in moist terrestrial habitats or near water, such as wetlands and ponds.

The breeding period for this species extends from January through June (Figure 45), with breeding occurring later at higher elevations. Breeding vocalization ceases at air temperatures below 41°F (Washington State Department of Natural Resources 2005). Eggs are deposited in shallow water (depth 4 to 30 in), attached to sticks, leaves, vegetation, or other objects. Temporary pools, isolated from the main channel flow, with dense submerged or emergent vegetation, are preferred (CDFG 1988). Eggs hatch in 1 to 5 weeks (CDFG 1988);

tadpoles rear for 1.5 to 2.5 months (Washington State Department of Natural Resources 2005).



Prepared by D. Ashton

Figure 45. Pacific treefrog life history phenology. Shaded boxes indicate activity periods; darker shading suggests peaks in activity.

Benthic Macroinvertebrates

Aquatic benthic macroinvertebrate communities are a key component of river ecosystems (Erman 1996). Their high species diversity and productivity are often considered ideal integrators and indicators of river ecosystem health. Though not as charismatic as fish or frogs, they constitute a critical ecological linkage between primary production and fish. This study quantifies the role of the snowmelt hydrograph in sustaining good and highly productive aquatic macroinvertebrate habitats.

Aquatic macroinvertebrate life histories are incredibly diverse, if for no other reason than there are so many different kinds of aquatic macroinvertebrates. One grapefruit-sized cobble can be home to 30 or more taxa, ranging from water mites to predatory stoneflies (e.g., refer to Figure 65 in Ruttner 1963). Three insect orders, mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera), generally comprise a large portion of the macroinvertebrate species colonizing riffles. Collectively these three orders, called the *EPT species,* are used as indicators of water quality. Their life histories are highly variable and often strongly seasonal. Aquatic macroinvertebrates, inventoried from the Clavey River in 1984 (Fields 1984), had a high species diversity dominated by the EPT species, but with an unusually high abundance of stoneflies.

This project's one-year study did not have the budget or the timeframe for detailed aquatic macroinvertebrate studies. Quantification of hydraulically complex and highly productive aquatic macroinvertebrate habitats as functions of streamflow and water temperature was attempted without being species specific. This required focusing on the most productive segments of the river, generally in riffle habitats, while biasing the assessment toward the EPT species. The task was in establishing physical criteria for good, hydraulically complex macroinvertebrate habitat and "highly productive" macroinvertebrate habitat, and in devising a simple methodology for their quantification.

Good macroinvertebrate habitat has a complex physical structure potentially providing abundant and diverse microhabitats. A square foot of channelbed composed of cobbles and small boulders provides much more useable surface area for EPT macroinvertebrates than larger or smaller substrate sizes. The quality of this surface area is better, by creating a wider range of velocities next to the substrate surface and by providing many more crevices of various sizes for filter feeders to construct nets; the crevices also provide refuge for mobile grazers and predators. Ruttner (1963, 232–233) notes that if "moving water" invertebrate species are left in a slow current, many soon die even though the water is cold and saturated with oxygen: "In a rapid current, however, the formation of such exchange-hindering investitures [adhering silt and organic matter] is strongly curtailed, and the absorbing surfaces are continually brought into close contact with new portions of water as yet unutilized. In this manner, moving water promotes respiration and uptake of nutrients much more than quiet water of the same content; it is not absolutely but rather physiologically richer in oxygen and nutrients." While moving water is physiologically necessary, complex habitat for rearing and reproduction also requires velocity.

Physical complexity can lead to hydraulic complexity depending on the flow's depth and velocity. Generic habitat preference curves for the EPT species by Gore et al. (2001) specify a high habitat suitability (> 0.5) over velocity ranges of a 30 to 85 centimeters per second (cm/sec) and depth ranges of 15 cm to 35 cm.

A simple methodology was designed to define an ecologically informative variable for aquatic invertebrates. The desired variable had to account for widely ranging velocities in magnitude and distribution (i.e., hydraulic complexity) and the amount of habitat at a spatial scale relative to aquatic macroinvertebrates. This desired variable also had to account for time. Time is a complex variable by itself, incorporating changing daylight, streamflow, and stream temperature throughout the year. Aquatic macroinvertebrate productivity in temperate climates tends to peak in late-spring when daylight and stream temperatures are increasing (Hynes 1970). An ecologically important process that snowmelt flows might provide is the creation of abundant, high-quality macroinvertebrate habitat when water temperatures favor high productivity.

For expert habitat mapping of macroinvertebrates in riffle-like environments (e.g., high flows on a cobble bar will be riffle-like), preferred depths were scaled to the size of the cobbles and small boulders (ranging from baseballs to basketballs). Flow depths from 2/3 the exposed substrate height to twice the exposed substrate height were mapped as productive macroinvertebrate habitat, if surface velocities ranged between 1 ft/sec and 3.5 ft/sec. These criteria were developed by observing a wide combination of depths, velocities, and particle sizes that represent macroinvertebrate activity and hydraulic complexity. A zone described by Ruttner (1963, 230) was observed in the Clavey River at surface velocities of 1 ft/sec and higher (if the substrate was small cobble and relatively shallow): "The leeward edge of a submerged obstruction provides an especially favourable biotope against being washed away. The zone where the eddy that fills the dead water space separates from the main stream flowing down the valley is a zone that is almost free of current processes, according to Ambuhl (1959). This zone is often clearly marked by a row of animals on the substrate there… and in it likewise the first moss coverings are able to establish a foothold." These lines of caddisfly cases, and often lines of Hydropsychid nets, served as bio-indicators for hydraulic complexity.

Water temperature is a dominant environmental factor for aquatic invertebrates; water temperatures can be too cold and too warm. Highly productive macroinvertebrate habitat therefore requires establishing a range of highly favorable water temperatures. Although the scientific literature provides numerous references and studies on upper thermal tolerances, surprisingly few references were found for optimal or highly favorable water temperatures for stream macroinvertebrates. In part, this omission is due to the wide range in thermal tolerances/preferences exhibited by the wide range of macroinvertebrate orders and families that typically live on the streambed. Stoneflies are generally more sensitive to higher water temperatures than mayflies, while mayflies are generally more sensitive than caddisflies, although many exceptions exist. A range of temperatures bounded by upper and lower thresholds is simplistic (i.e., EPT productivity would not cease outside these water temperature thresholds) but useful for exploring this hypothesis.

A daily average temperature range of 41°F to 55°F was adopted as highly productive for macroinvertebrates, based on individual species studies and agency guidelines, particularly those by the Washington State Department of Ecology (2002).

3.4. Synthesis

Having collected and analyzed the hydrologic, geomorphic, and ecological characteristics of the Clavey River and Cherry Creek, synthesizing this information into pulse flow recommendations will fulfill Project Objectives 2 and 3 (Section 1.2). As detailed in the synthesis methods (Section 2.5), synthesis is largely accomplished graphically.

3.4.1. Synthesizing Seed Dispersal and the Annual Hydrograph

The seed dispersal period for common riparian hardwood species was compared to the WY2005 hydrograph of the Clavey River (Figure 46). Dispersal primarily occurs in the spring, during the snowmelt recession period. This analysis is particularly important because the relationship determines the spatial extent of seed dispersal, assuming that seeds are transported be receding flows. If flows are higher in a particular water year, then seeds will be transported higher up the channel sides, into the floodplains.

3.4.2. Synthesizing Seedling Initiation, Stage Height, and Scour Thresholds Through Recruitment Box Modeling

Woody riparian vegetation dynamics were modeled at two locations within the Clavey River mainstem: (1) Cottonwood Bar, a large point bar that encompasses several boulder ribs, represented by XS 16+33 (Figure 9), and (2) a small point bar nestled between a pair of boulder ribs, represented by XS 32+62 (Figure 10). Using the five selected runoff years (WY2005 (Extremely Wet), WY1973 (Wet), WY1971 (Normal), WY1968 (Dry), and WY1976 (Critically Dry) (Figure 15, Section 2.4.4), seedling initiation and early establishment were modeled, asking: (1) Did successful initiation occur during any or all sample water years on both or either point bar, and (2) if successful initiation did occur, could these successfully initiated seedlings have survived their first winter floods and second snowmelt flows? Seedling initiation and scour were modeled using the recruitment box model (Section 2.4.8)

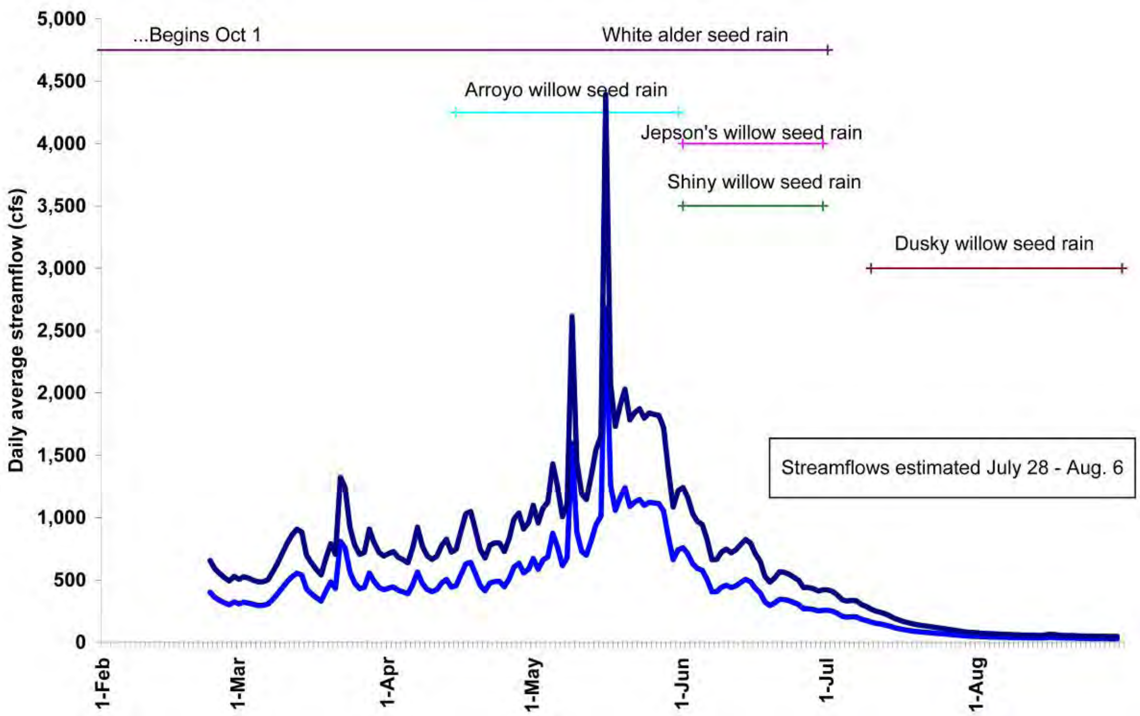


Figure 46. Seed dispersal periods for common riparian hardwoods related to the WY2005 Clavey River hydrographs. Blue hydrograph indicates study site near the 1N04 bridge gage, and the black hydrograph indicates the USGS Gaging Station No. 11283500, Clavey River at Buck Meadows.

and the threshold flood estimates for seedling scour at different locations along XS 16+33 and XS 32+62 (Appendix E).

In the mainstem Clavey River, on large and moderately sized depositional features, such as Cottonwood Bar and the small point bar on XS 32+62, respectively, successful initiation is due largely to how the receding snowmelt hydrograph regulates stage height during the willows' seed release and early growth periods. What a seedling experiences is not streamflow, but water stage (inundation) and soil moisture (Figure 47). The light gray water lines record the stage heights of the entire WY2005 snowmelt recession limb in one-week intervals. When the water lines (stage heights) are close together, the rate of water surface decrease is slow. When the lines are closely spaced, seedlings are less challenged to grow roots sufficiently quickly to keep pace with receding streamflows (and soil moisture). In WY2005, this situation occurs only briefly at an elevation of 96 ft, but for an extended time (longer than a month) at 93.5 ft (Figure 47). Widely spaced stage height lines mean that seedlings desiccate and die. In WY2005, the optimum strategy was to release viable seeds late in the snowmelt runoff hydrograph (Figure 46) to land on the "lower bar flank" and/or the "lower middle bar" of the point bar represented by XS 16+33 (Figure 47). In WY2005 on XS 16+33, dusky willow's seed release period is relatively late-season, but lengthy; it is the only willow species that could successfully initiate (i.e., germinate and survive up to the winter).

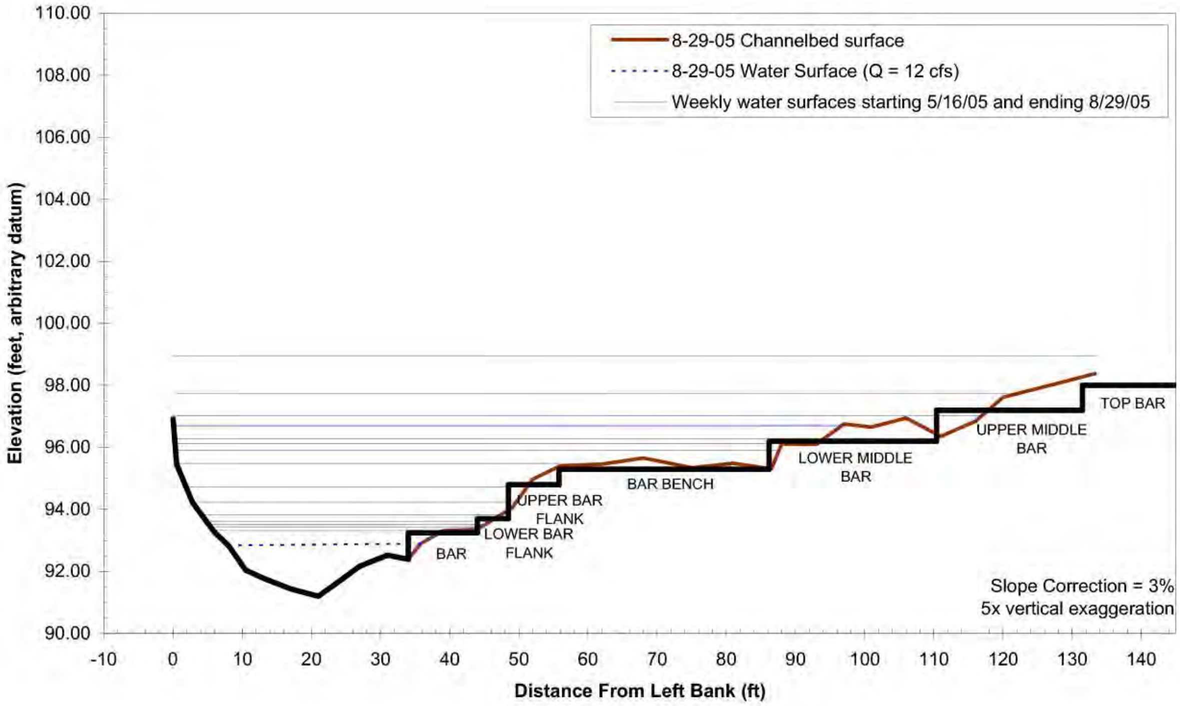


Figure 47. Stage change resulting from snowmelt runoff measured at 7-day intervals at the Clavey River's cross section 16+33; the highest water surface was measured on May 16, 2005.

Along XS 16+33 (representing a large point bar like Cottonwood Bar) and XS 32+62 (representing a small point bar between boulder ribs), each point presents unique risks to germinating seedlings. Beside the risk of desiccation, which depends on a particular snowmelt hydrograph, there is the risk of scour. Entering their first winter, seedlings must survive winter floods and then survive the next spring's snowmelt peak flows. For discrete surfaces along both cross sections, scour thresholds were estimated by calculating a shear stress two-times (double) that predicted to mobilize the D_{84} of the channelbed. In the field, these estimates equate to flood flows greater than 5 ft deep at slopes of 0.025 to 0.035. Young seedlings were rooted in the matrix between the larger particles represented by the D_{84}. On XS 16+33, the scour thresholds for young seedlings ranged from a 1.5-yr flood of 1300 cfs at the bar's edge up to a 17.5-yr flood of 15,000 cfs; on XS 32+62, scour thresholds ranged from a 1.3-yr flood of 900 cfs up to a 3.8-yr flood of 3700 cfs (Table 13).

Along the large point bar of cross section XS 16+33, successful initiation was possible in all sample runoff years for dusky willow and for Jepson's willow in the drier runoff years at the point bar's edge and lower bar flank (i.e., close to the summer baseflow shoreline). None survived through the first summer higher up on this Cottonwood Bar cross section. Early establishment may have occurred in RY1971 (Normal) and RY1976 (Critically Dry) for dusky willow and for Jepson's willow in RY1976. Seedlings in both runoff years were likely scoured away in RY1980's 17-yr winter flood peak.

Table 13. Scour thresholds and flood recurrences for young seedlings along XS 16+33, a large point bar on Cottonwood Bar, and along XS 32+62, a small point bar between a pair of boulder ribs, on the Clavey River.

	Threshold flood (cfs)	Flood recurrence (yr)
XS 16+33 Cottonwood Bar		
Bar edge	1,300	1.6
Lower bar flank	2,000	2.3
Upper bar flank	2,900	3.3
Bench	3,700	3.8
Lower middle bar	7,000	7.0
Upper middle bar	9,500	10
Top of bar	15,000	17
XS 32+62 small point bar between boulder ribs		
Bar flank	1,300	1.6
Lower lee deposit	1,200	1.5
Upper lee deposit	1,200	1.5
Lower point bar	1,800	2.0
Upper point bar	2,700	3.3
Upper bar	3,700	3.8

Along the small point bar between boulder ribs represented by cross section XS 32+62, successful initiation occurred at several points for dusky willow and Jepson's willow. The relief of the small point bar on XS 32+62 was much less than that of Cottonwood Bar, and would account for moisture being more readily available for seed germination and early growth (i.e., its bed surface is closer in elevation to the summer baseflow water surface than is most of the bed surface of Cottonwood Bar). Early establishment may have occurred in RY1971 (Normal) and RY1976 (Critically Dry) for dusky willow, and in RY1976 (Critically Dry) for Jepson's willow. Dusky willow seedlings initiating in RY1971, and achieving early establishment entering their second winter of RY1973 (Wet), might have been scoured away in WY1973's 3-yr winter flood peak. All seedlings would have been scoured away by WY1980's 17-yr winter flood peak.

White alders were not modeled for initiation or early establishment. Their seed release period lasts longer than a year because their seeds remain viable longer than a year. Seeds are generally rafted along debris lines following winter and snowmelt floods. Once germinated, white alder seedlings must undergo the same hurdles of desiccation and scour as encountered by willows.

3.4.3. Synthesizing Seedling Survival and Large Depositional Features

The white alders and willows that root on large bar features do so in a substrate that is generally finer than most of the channelbed. If the white alder and willow seedlings survive early removal, their roots continue to weave through and around the small boulders composing the bar's sub-surface. If the boulders themselves are not mobilized, the boulders anchor the trees. As demonstrated in the photographs analyzed for geomorphic mobility, many small boulders were hydraulically hidden among larger boulders, and so were not moved by the January 1997 flood. But, if a tree is associated with a boulder, and the tree protrudes up into the flood flow, the boulder is more susceptible to the flood's physical forces. The tree/boulder association may not be a good strategy for the alder either (Figure 48). As the tree grows, it accumulates mass and its stem, now a trunk, becomes more rigid. At approximately eight years (under good growing conditions), their four- to six-inch diameter trunks have gradually become too rigid to gracefully flex during floods. A physical analysis might identify the moment of failure (similar to estimating the tensile force a rigid crowbar might absorb before it breaks). As the tree becomes more rigid and heavier, its risk of being uprooted may increase even at equal flood magnitudes.

Given the difficulty of initiating and becoming established on bar surfaces, the row of white alders in WY1993 on Cottonwood Bar represents a number of processes that occurred in favorable order and magnitude (Figure 41). The photograph shows the trees positioned immediately below a boulder rib only partially buried by the point bar's smaller boulders and cobbles. During high floods, the water spills over the boulder rib and scours up to 1.5 to 2.0 ft deep holes (Figure 49). These scour holes are ideally suited for germinating willows and alders. During the fast snowmelt recession limb, viable seeds that are transported into the holes experience extended and steady access to moisture, rather than rapidly changing moisture conditions on the bar's surface. However, although the chances of successful initiation are higher, seedlings would also experience greater risk of scour, when flood flows again spill over the boulder rib and re-scour the holes. Prior to WY1993, conditions were ideal for seedling survival (Figure 40). As these scour hole trees mature, they are unlikely to survive scour from high flows. All old alders are located either on the inside of sharp channel bends, in the lee of bedrock ridges projecting into the active channel, or behind large protecting boulders.

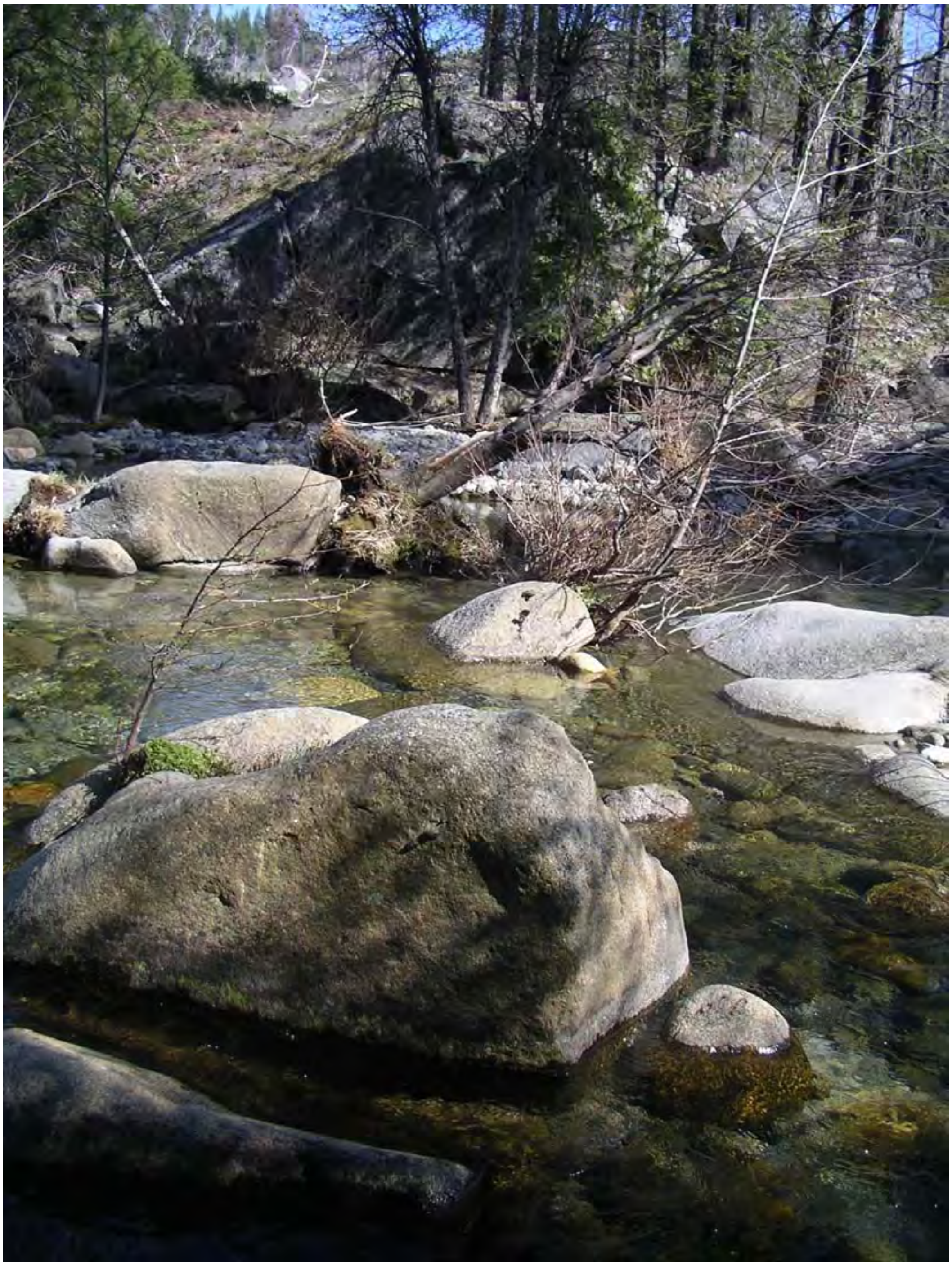


Figure 48. Mature white alder rotated out of bank. This photo was taken on Cherry Creek in 2005.

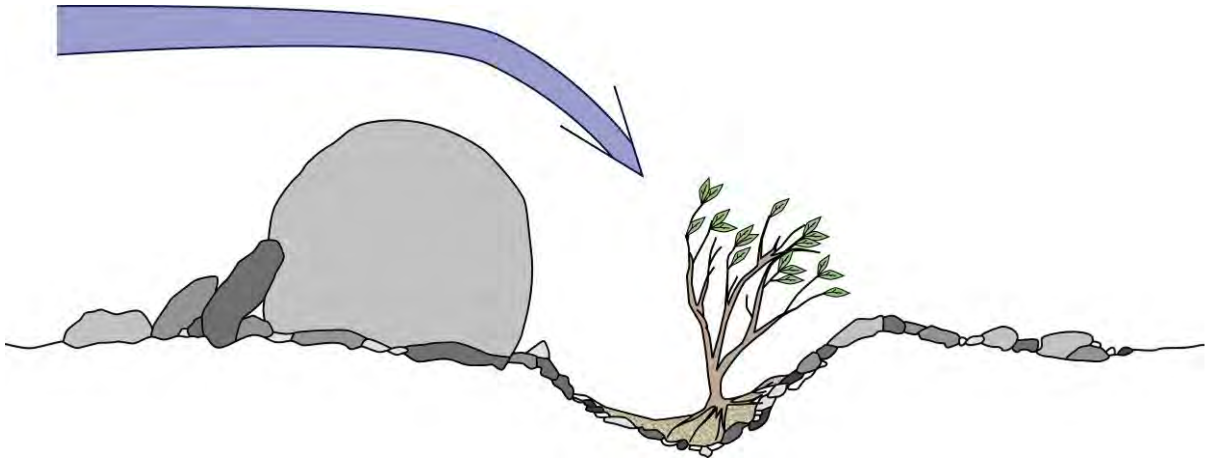


Figure 49. Scour holes below a boulder rib.

3.4.4. Synthesizing Rainbow Trout Habitat, Daily Flows, the Snowmelt Hydrograph, Scour, and Desiccation

Snowmelt flows transition from winter to summer just when trout embark on another cycle of reproduction and growth. The marked increase in habitat availability, which is due to snowmelt flows, signals the approach of spring and likely affects how fish populations will fare. These relationships are quantified by constructing spawning and fry habitat rating curves, which along with snowmelt hydrographs, allows construction of habigraphs. After consideration of rainbow trout life stage timing, relative habitat abundance, and temperature thresholds, annual habigraphs are used to construct reference condition curves for recommending pulse flow guidelines that prescribe the snowmelt flows required to fill many ecological roles.

Rainbow Trout Spawning and Fry Habitat Rating Curves

At the Clavey River study site, expert habitat mapping documented limited rainbow trout spawning habitat for most flows (see light blue patches in photographs of Figures 50 and 51; Figure 52). At Cottonwood Bar, during baseflows, spawning habitat was limited to a small patch (< 300 ft^2) at the upstream end of the bar; during the rapid snowmelt recession and early in the slow snowmelt recession flows, spawning habitat was limited to a few patches (totaling 156 ft^2) on the bar surface. In the boulder sub-reach, spawning habitat was < 320 ft^2 (< 0.1 ft^2/ft of channel) for most of the snowmelt recession flows. At 57 cfs, at the middle or near the end of the slow snowmelt recession limb (depending on runoff year type), mapped habitat increased to 1596 ft^2 (0.7 ft^2/ft of channel) as lee and pool/run tail deposits became shallow and slow enough for spawning (Table 14).

Expert habitat mapping documented abundant fry-rearing habitat at the Clavey River study site, over a broad range of flows (see dark blue patches in photographs of Figures 50 and 51; Figure 53).

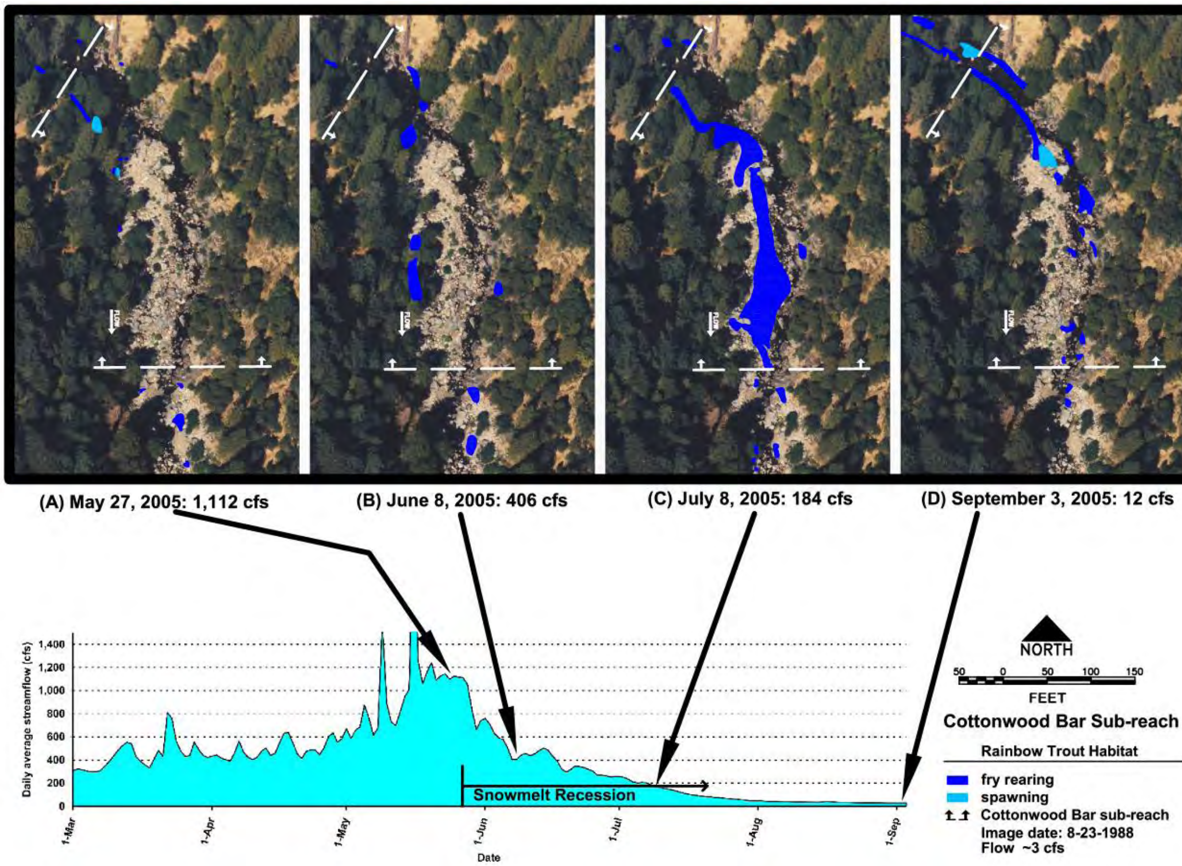


Figure 50. Rainbow trout habitat polygons from expert habitat mapping at 1112 cfs, 406 cfs, 184 cfs, and 12 cfs in the Clavey River study site, Cottonwood Bar sub-reach.

At Cottonwood Bar, fry-rearing habitat was most available when the bar was just being inundated (i.e., when flow depth over the bar was shallow and flow velocity was low); fry-rearing habitat area was highest at 6941 ft^2 when flow was 184 cfs (Table 15, Figure 53). When the bar surface was suitable for fry rearing, habitat density reached 18.1 ft^2/ft of channel, which is an order of magnitude greater than habitat density in the boulder sub-reach for the same flow (2.8 ft^2/ft). As flow increased beyond approximately 500 cfs, flow across the bar's open cobble/small boulder expanses becomes too fast for fry rearing, so mapped habitat area decreases to 142 ft^2 at 1112 cfs. Another habitat mapping survey at 450 cfs to 500 cfs would likely have shown an even steeper habitat area decrease than that shown in Figure 53.

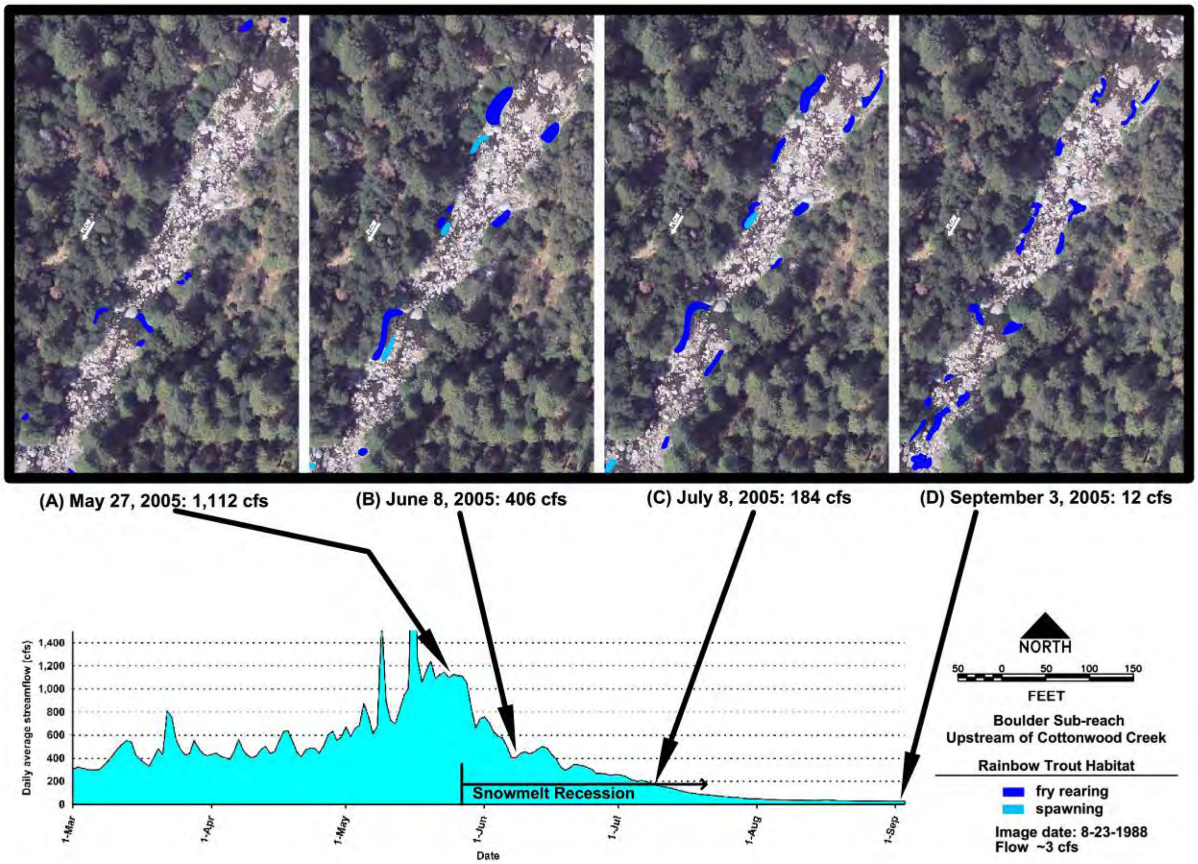


Figure 51. Rainbow trout habitat polygons from expert habitat mapping at 1112 cfs, 406 cfs, 184 cfs, and 12 cfs in the Clavey River study site, boulder sub-reach.

Table 14. Rainbow trout spawning mapped habitat area in the Clavey River study site.

Daily avg. flow at 1N04 (cfs)	Mapped habitat area (ft^2)			Habitat density (ft^2/ft)		
	Entire study site	Cottonwood Bar sub-reach	Boulder sub-reach	Entire study site	Cottonwood Bar sub-reach	Boulder sub-reach
1,112	156	156	0	0.1	0.4	0.0
406	319	0	319	0.1	0.0	0.1
184	216	0	216	0.1	0.0	0.1
57	1,834	238	1,596	0.7	0.6	0.7
12	575	301	274	0.2	0.8	0.1

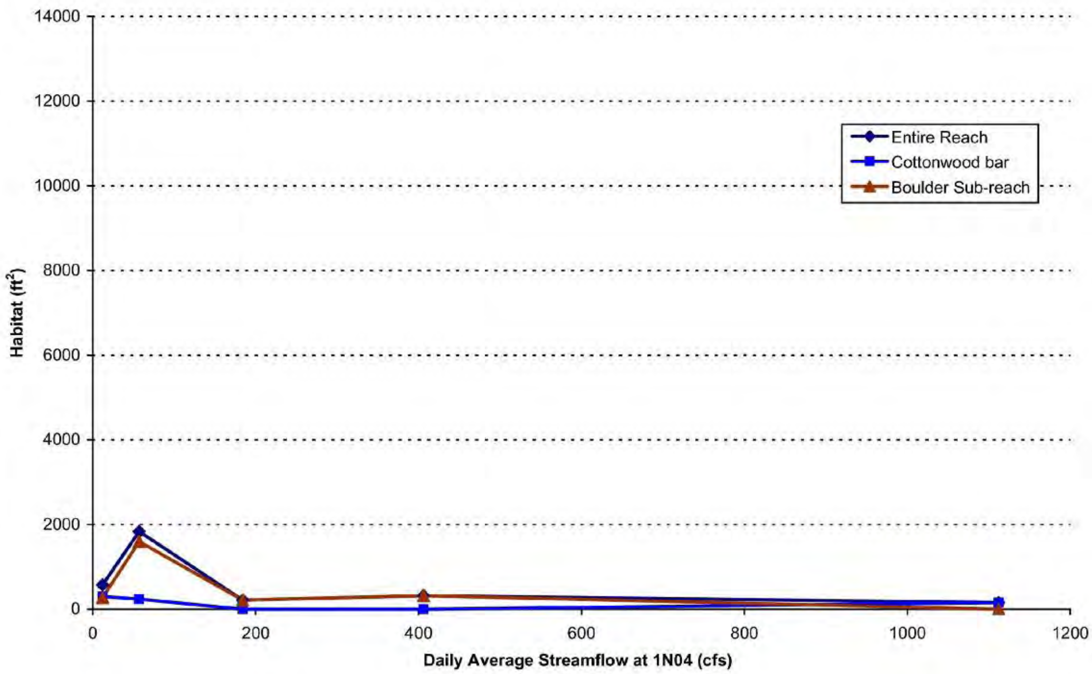


Figure 52. Rainbow trout spawning habitat rating curve for the Clavey River study site.

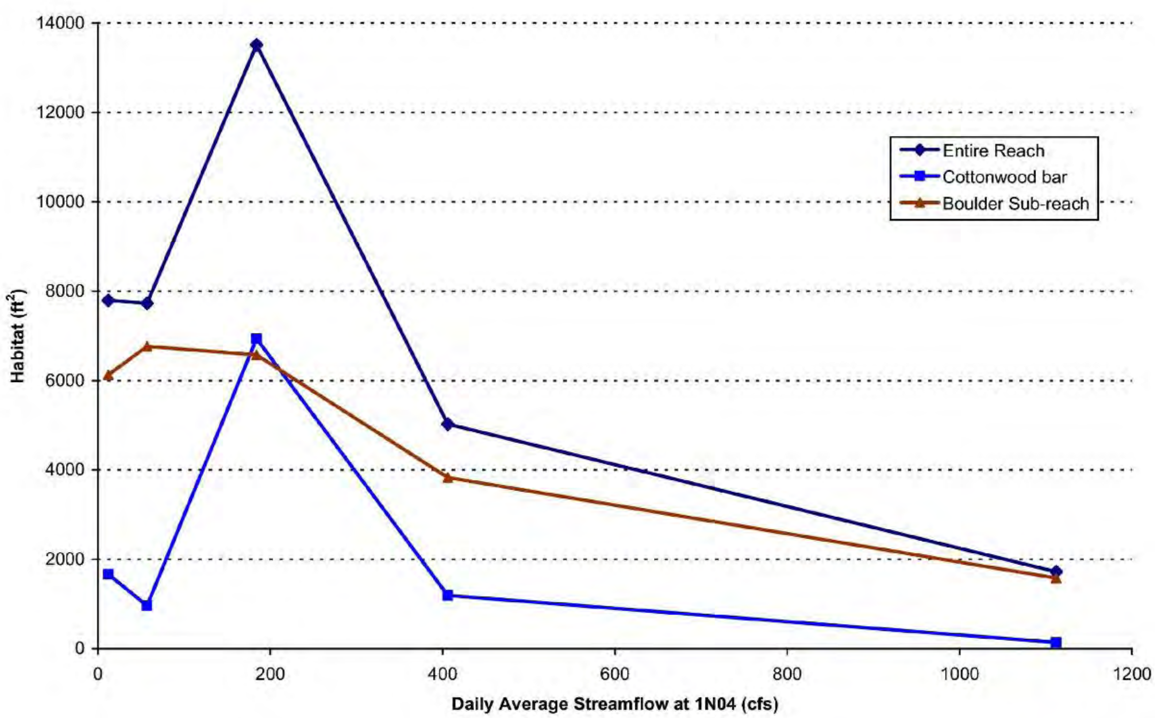


Figure 53. Rainbow trout fry-rearing habitat rating curve for the Clavey River study site.

In the boulder sub-reach, mapped fry-rearing habitat area exceeded 6000 ft^2 during slow recession flows (flows 12 cfs to 184 cfs) then declined gradually to 1581 ft^2 at higher snowmelt recession flows (Table 15). Most habitat occurred along the channel margins, often associated with lee deposits between boulder ribs. With increasing flow above 12 cfs, rearing habitat shifted location with the rising stage. Wider segments of the bedrock/boulder reach, with more spacing between boulder ribs and gentler slope, produced several extensive rearing habitat patches between 57 cfs and 184 cfs, which are flows occurring during the slow snowmelt recession limb of wetter runoff years, and during the fast snowmelt recession limb of drier runoff years. Rainbow trout fry rearing habitat overlapped with California roach fry habitat.

Table 15. Rainbow trout fry mapped rearing habitat area in the Clavey River study site.

Daily avg. flow at 1N04 (cfs)	Mapped habitat area (ft^2)			Habitat density (ft^2/ft)		
	Entire study site	Cottonwood Bar sub-reach	Boulder sub-reach	Entire study site	Cottonwood Bar sub-reach	Boulder sub-reach
1,112	1,724	142	1,581	0.6	0.4	0.7
406	5,028	1,194	3,833	1.9	3.1	1.7
184	13,517	6,941	6,576	5.0	18.1	2.8
57	7,733	965	6,769	2.9	2.5	2.9
12	7,797	1,666	6,131	2.9	4.3	2.7

Rainbow Trout Spawning and Fry Habigraphs

To define ecologically available spawning habitat area, two biological thresholds are required: (1) favorable channel bed substrate and flow properties (depth and velocity), and (2) favorable temperatures. The EHM identified rainbow trout spawning habitat based on depth, velocity, and substrate. The second threshold, the temperature that initiates spawning, was needed to establish potential dates for redd construction and spawning. McCullough (1999) identifies the optimal temperature range for rainbow trout spawning as 50°F to 54°F. Within this range, hatching success (keeping temperature constant) is expected to exceed 90%. As temperature exceeds this range, hatching success decreases steadily, eventually reaching 10% at 59°F (McCullough 1999). As predicted by the SNTEMP model (Section 2.3.1), weekly average temperatures were used for all runoff years except RY2005, and the range of temperatures was widened to include less than optimal conditions; the spawning temperature threshold range increased from 47°F to 59°F for this analysis. This spawning temperature threshold range was used to establish the first possible spawning date in each sample runoff year (Table 16).

Table 16. First possible dates for which spawning can be initiated, based on temperature thresholds for each selected runoff year, on the Clavey River.

Runoff year type	Spawning threshold date			
	@ 47°F	@ 50°F	@ 54°F	@ 59°F
RY1976 (Critically Dry)	April 28	May 03	May 17	June 10
RY1968 (Dry)	April 25	May 25	May 28	June 13
RY1971 (Normal)	May 20	June 08	June 21	July 06
RY1973 (Wet)	April 26	May 11	June 07	June 25
RY2005 (Extremely Wet)	May 22	June 01	June 19	June 27

Water temperature and species temperature thresholds were superimposed on the rainbow trout spawning habigraphs for each selected runoff year (Figures 54 to 58) to compute reference conditions in formulating pulse flow recommendations.

Because most spawning habitat was available only at lower flows, ecologically available spawning habitat was generated during the slow snowmelt recession limb in four of the five runoff year types. Cottonwood Bar had too few gravel deposits to exhibit abundant spawning habitat, even when the bar was inundated by snowmelt flows. For Normal and wetter runoff years, spawning habitat was not available until late June or mid-July, which is at or after the end of the trout spawning window, once water temperature is considered. In Dry and Critically Dry years, snowmelt runoff peaked early in the season and its magnitude was low. In these drier years, ecologically available spawning habitat occurred in the mainstem during the trout spawning period. In the Critically Dry runoff year (RY1976), spawning habitat became ecologically available in early April. In the Dry runoff year (RY1968), spawning habitat became ecologically available in late May, occurring at small lee and pool/run tail deposits in the boulder sub-reach. For all runoff years, ecologically available spawning habitat in the study site was sparse, generally occurring at small lee and pool/run tail deposits in the boulder sub-reach. With poor spawning conditions in the mainstem during most years, rainbow trout spawn primarily in tributaries (Tuolumne County and TID 1990). The role of the mainstem, relative to the tributaries, may change year-to-year. In Dry years, when access to tributaries is more difficult, the mainstem may be more important for spawning and fry production.

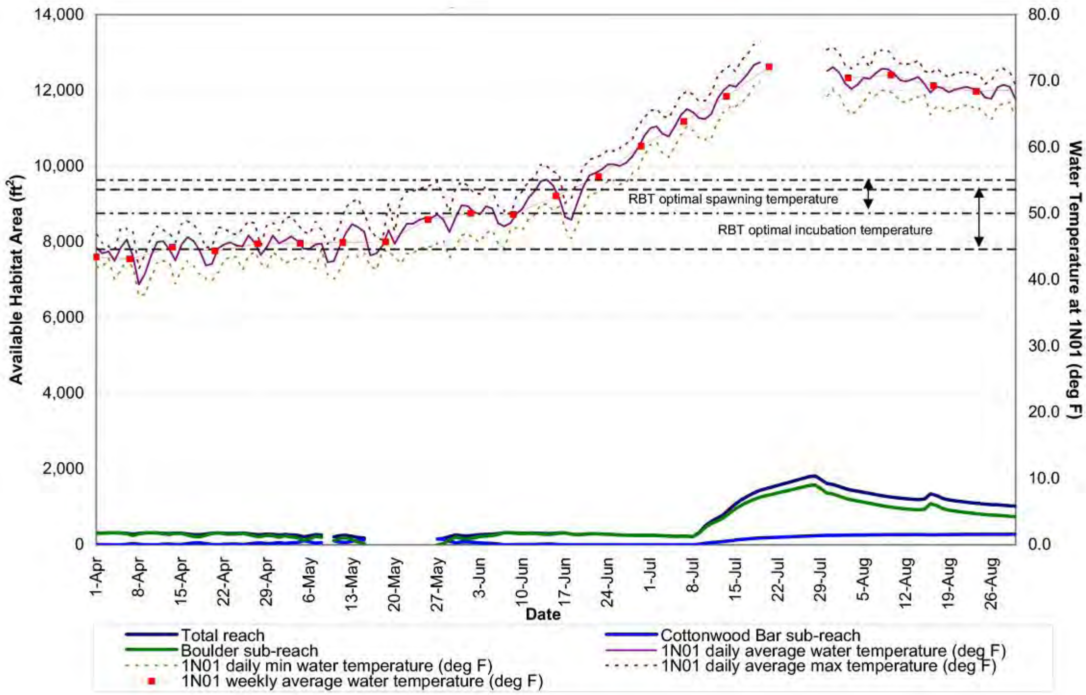


Figure 54. Habigraph for rainbow trout spawning at the Clavey River study site, RY2005 (Extremely Wet).

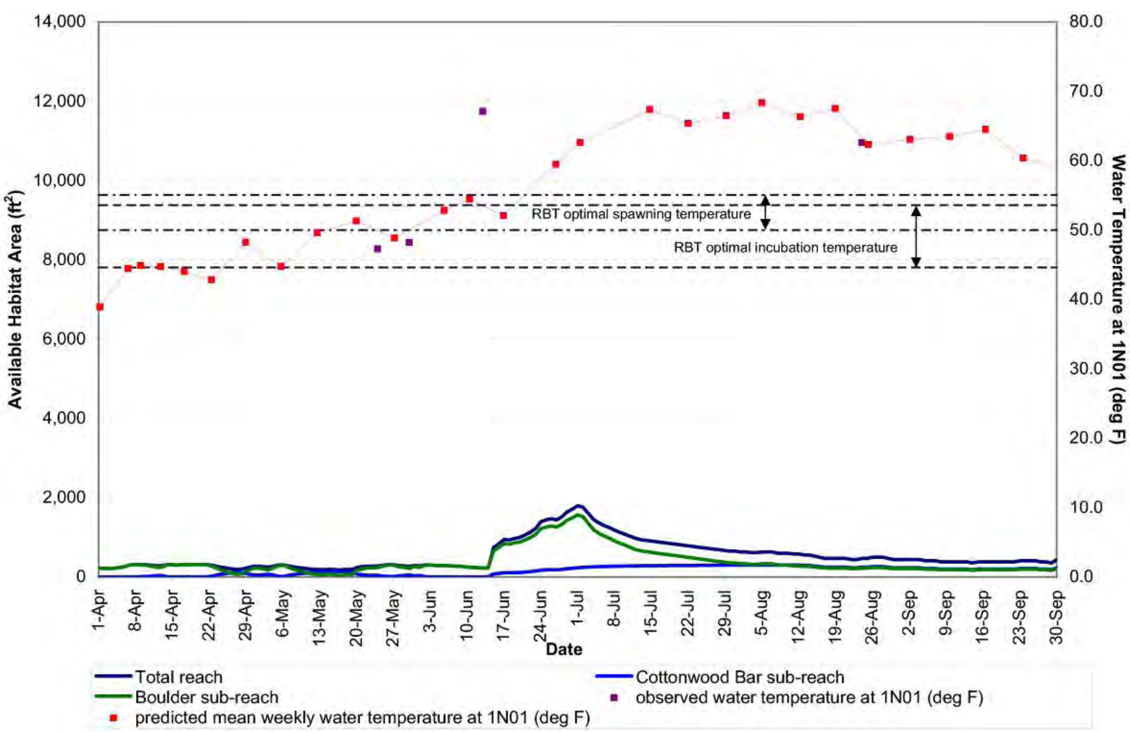


Figure 55. Habigraph for rainbow trout spawning at the Clavey River study site, RY1973 (Wet).

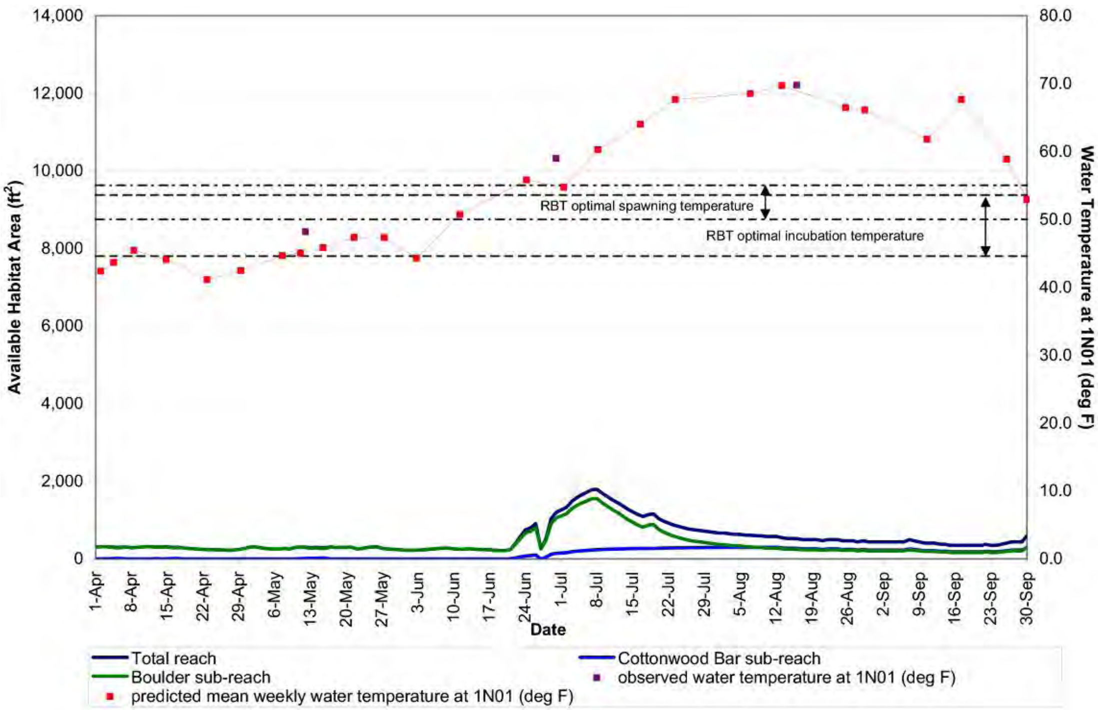


Figure 56. Habigraph for rainbow trout spawning at the Clavey River study site, RY1971 (Normal).

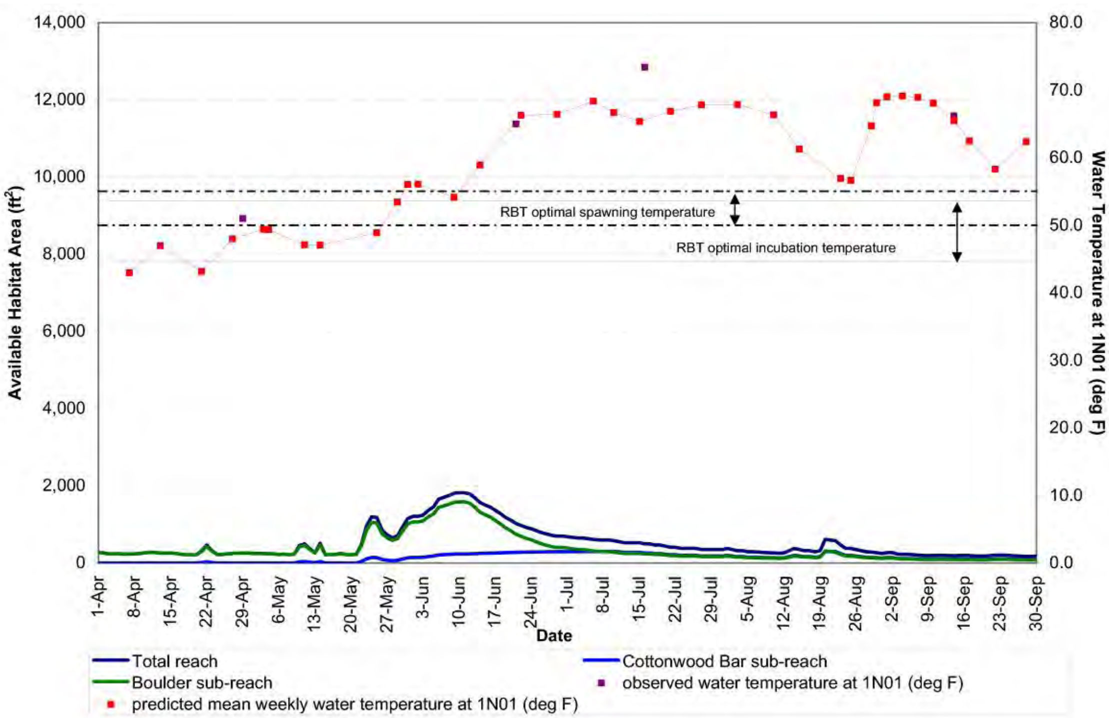


Figure 57. Habigraph for rainbow trout spawning at the Clavey River study site, RY1968 (Dry).

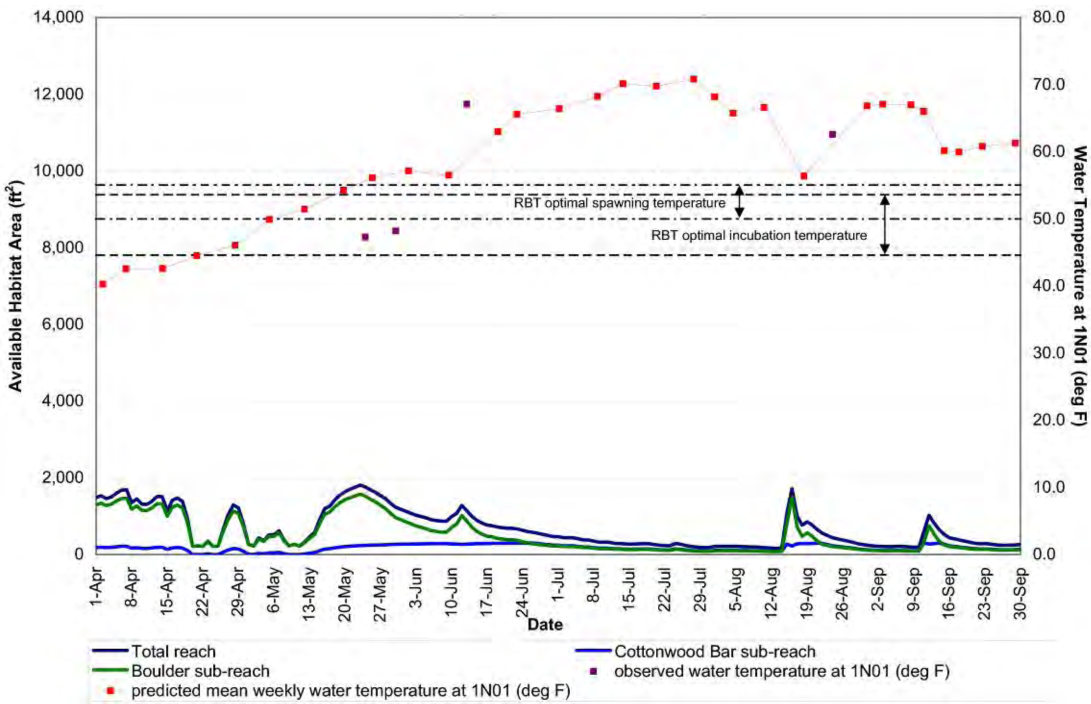


Figure 58. Habigraph for rainbow trout spawning at the Clavey River study site, RY1976 (Critically Dry).

Windows of typical fry emergence were superimposed onto habigraphs for each of the selected runoff years (Figures 59 to 63). In Critically Dry, Dry, and Normal runoff years, the boulder sub-reach and/or Cottonwood Bar sub-reach provided ecologically available fry habitat in April and May, then produced less habitat in June, when most habitat originated in the boulder sub-reach. In Wet and Extremely Wet water years, high streamflows decreased fry habitat area in both sub-reaches during April and May. When the snowmelt recession flows began, ecologically available fry habitat area increased then decreased rapidly due to the narrow streamflow window of Cottonwood Bar.

Timing of fry available habitat area could be more important than the amount of habitat. Fry habitat area is important only when fry are present. Successful mainstem spawning likely occurs during the slow snowmelt recession flows, just when water temperatures are rapidly rising (Figures 54 to 58). So fry habitat in April and May would not be heavily used or needed except by those fry produced by early spawning in the tributaries. Fry produced in the mainstem would emerge later, from early June through early July. However, in drier years, fry habitat area is already decreasing by early June. In an Extremely Wet runoff year, fry habitat area is increasing when fry are likely to emerge, but stream temperatures begin to rise steeply. Considering relative habitat abundance, temperature thresholds, and life stage timing, the Normal runoff year is the most favorable runoff year type for fry. In the Normal runoff year, habitat is abundant and water temperatures are highly favorable when fry are emerging and during early growth. Throughout April and May, flows sufficiently inundate Cottonwood Bar, but not by too much, creating habitat; in the boulder-bedrock sub-reach, these flows complement fry habitat.

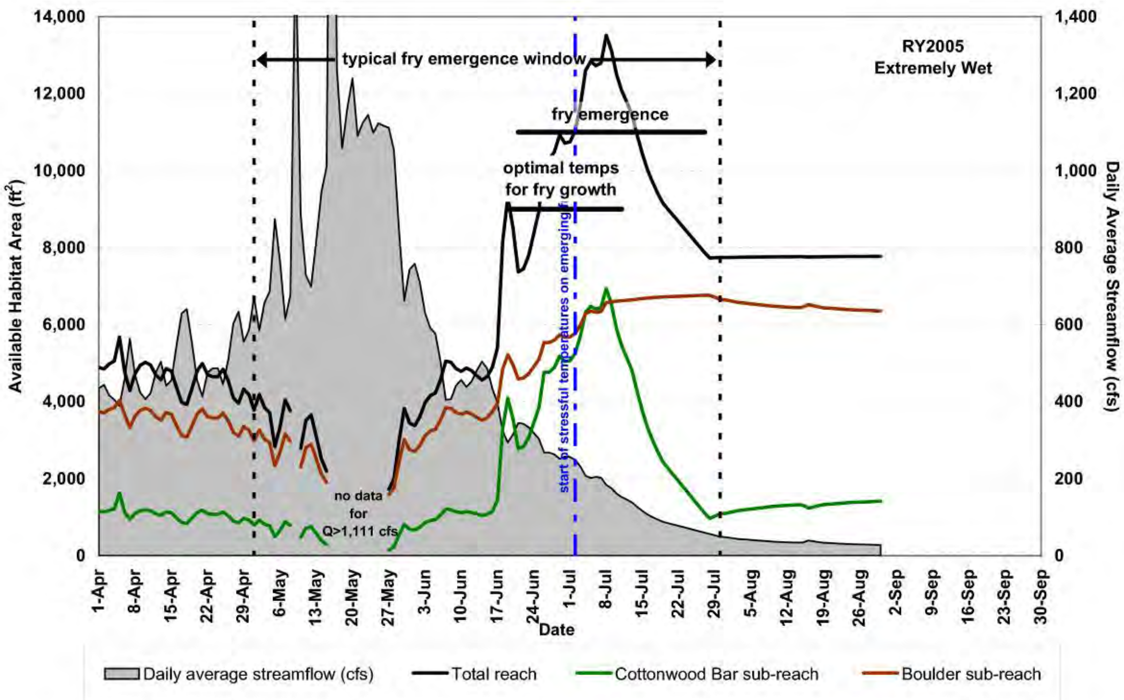


Figure 59. Habigraph for rainbow trout fry rearing at the Clavey River study site, RY2005 (Extremely Wet).

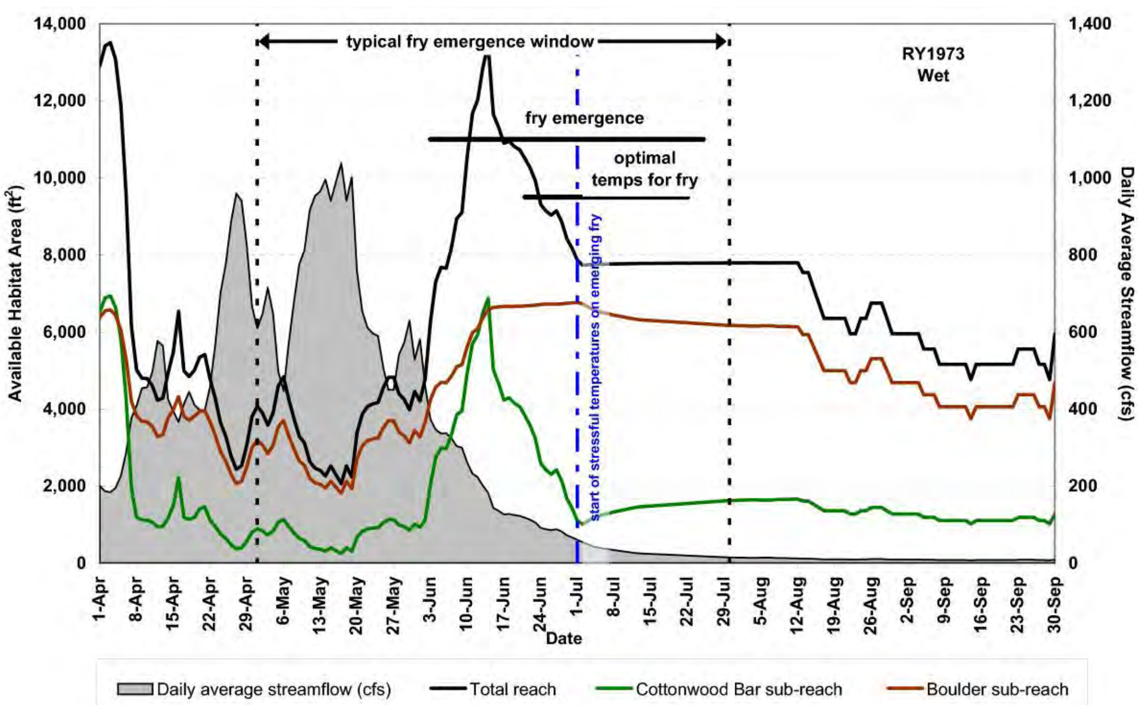


Figure 60. Habigraph for rainbow trout fry rearing at the Clavey River study site, RY1973 (Wet).

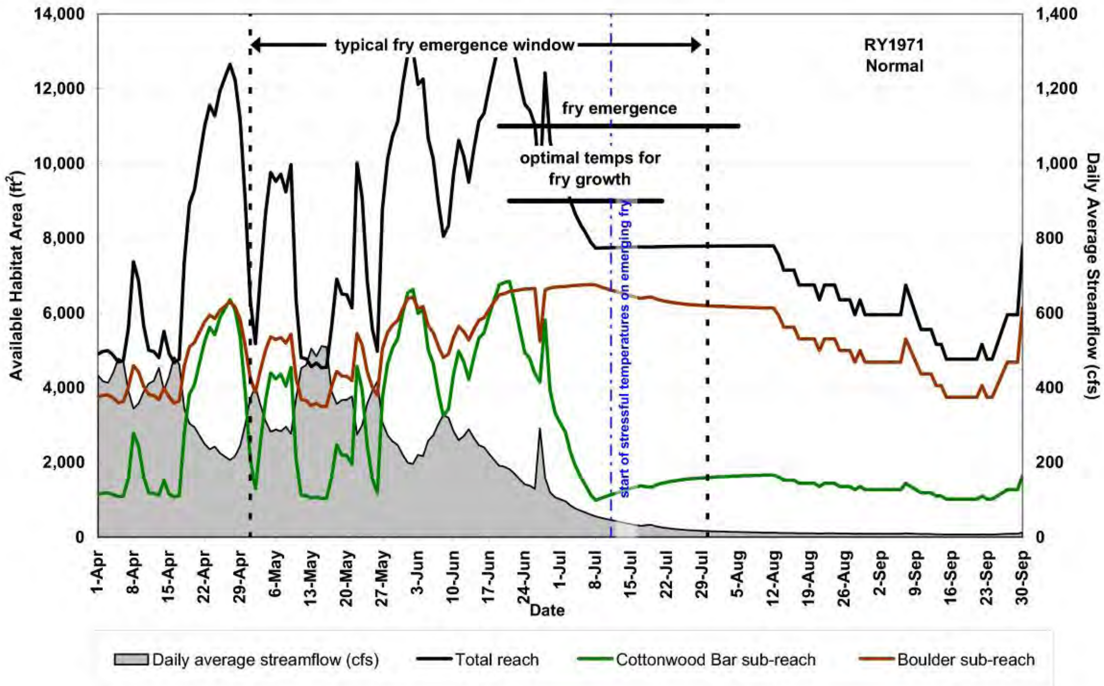


Figure 61. Habigraph for rainbow trout fry rearing at the Clavey River study site, RY1971 (Normal).

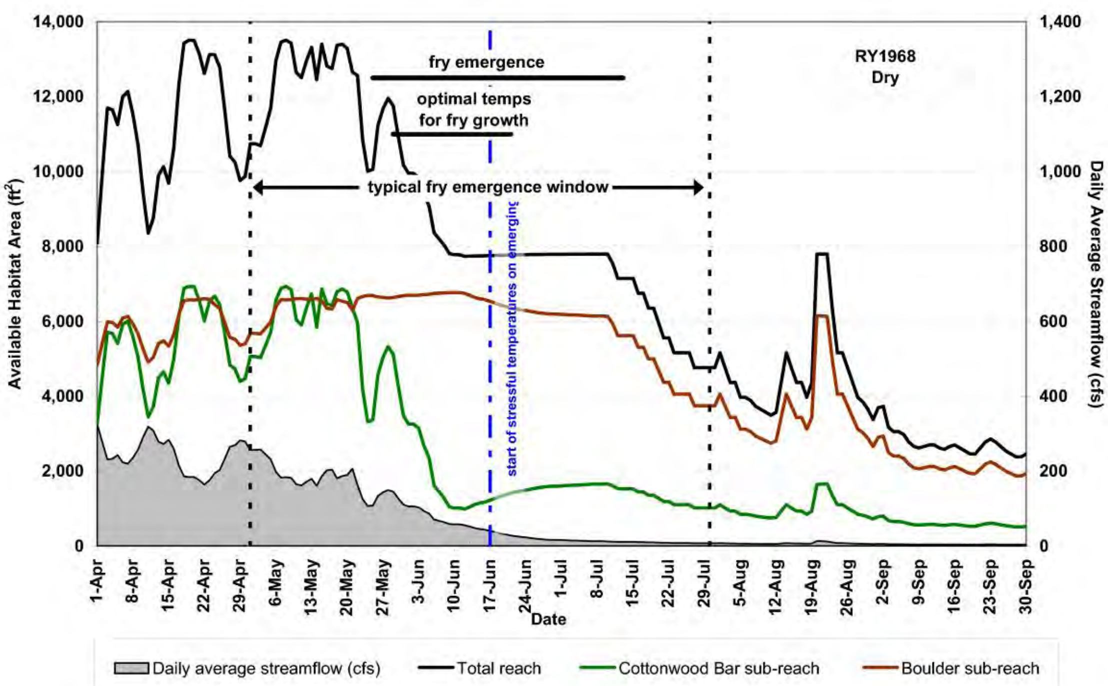


Figure 62. Habigraph for rainbow trout fry rearing at the Clavey River study site, RY1968 (Dry).

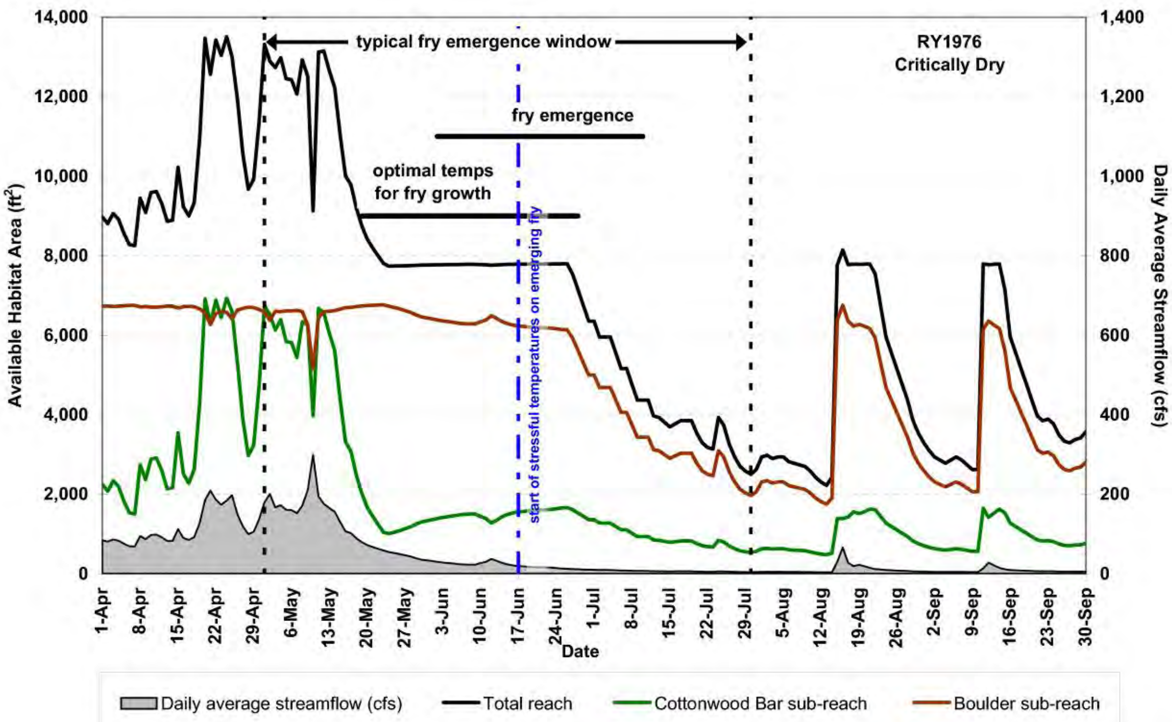


Figure 63. Habigraph for rainbow trout fry rearing at the Clavey River study site, RY1976 (Critically Dry).

Rainbow Trout Redd Desiccation and Scour Risk

Rainbow trout eggs deposited 0.5 ft below the mainstem channelbed's surface either survive if flows are "right," or die if scoured by high flows during the snowmelt peak or if abandoned by low flows during the slow snowmelt recession flows. In this study, egg survival, or spawning risk, was considered a binary event: either the eggs hatched successfully or they did not. A simple model was developed to assess whether redd scour or redd desiccation would occur in specific spawning deposits during the selected runoff years.

Rainbow trout typically spawn in finer depositional features located at the tails of pools and runs. These gravel deposits are close to the thalweg, and their bed elevations are not much higher than the thalweg elevation. While unlikely to be desiccated, redds constructed in these run/pool tails are susceptible to scour. Spawning risk was modeled in three spawning habitat patches mapped during the 2005 habitat surveys. These three patches were located in widely varying depositional features. One patch was in a run tail within a boulder rib sequence on XS 32+62. The second patch was a lee cobble deposit within a boulder rib sequence on XS 32+10. The third patch was on the upstream margin of Cottonwood Bar on XS 17+53; this point bar spawning patch was sloped gently toward the thalweg, and thus was spawnable over a wide range of streamflows (as opposed to the first two patches that were essentially flat and had narrow windows of spawnable flows). At the third patch, lower and upper potential spawning sites were assessed independently.

Temperature thresholds indicate when spawning is highly probable, but flow depth and velocity at the depositional features that provide spawnable gravel have to be suitable to attract spawning fish. Based on preferred depth and velocity, a window of spawning opportunity (as was used in the expert habitat mapping) was established at each spawning habitat patch (Table 17). Streamflows above and below this window were either too fast and/or deep or too slow and/or too shallow for spawning.

Table 17. Flows during spawning window of opportunity on the Clavey River.

Depositional feature	Highest streamflow (cfs)	Lowest streamflow (cfs)
Run tail	125	10
Lee cobble deposit	400	250
Point bar - lower	400	225
Point bar - upper	800	550

In a particular depositional feature, successful spawning occurs during depth and velocity spawning preferences, and deposited eggs avoid scour and remain inundated past the incubation threshold (Table 18). Tables 17 and 18 constitute the risk model that was then applied to the five selected runoff years, to evaluate rainbow trout spawning success by runoff year type. In some runoff years, successful spawning days were few, while in others there were many (Table 19).

Table 18. Flow thresholds for redd desiccation and scour at three depositional features providing spawning habitat on the Clavey River.

		Scour thresholds	
Depositional feature	Desiccation threshold	Lower	Upper
Run tail	<10 cfs	250 cfs	600 cfs
Lee cobble deposit	175 cfs	700 cfs	2000 cfs
Point bar - lower	175 cfs	700 cfs	3000 cfs
Point bar - upper	420 cfs	2000 cfs	6000 cfs

Table 19. Successful spawning for rainbow trout in the mainstem Clavey River by runoff year type and depositional feature (Y = yes, if spawned, could have produced emergent fry; N = not spawnable or if spawned, the eggs would die due to redd scour or desiccation).

Runoff year type	Depositional feature			
	Run tail	Cobble deposit	Point bar-lower	Point bar-upper
Critically Dry	Y(44,23)	N	N	N
Dry	Y(21,21)	N	N	N
Normal	Y(08,08)	Y(25,05)	Y(27,07)	N
Wet	Y(06,06)	Y(18,07)	Y(18,08)	Y(02,00)
Extremely Wet	N	N	N	Y(08,00)

Y(x,y): x = number of successful spawning days
y = number of successful spawning days when eggs would have experienced a stressful weekly average temperature of 62°F or higher at the end of their incubation period

For rainbow trout under a constant water temperature of 62°F, studies have documented no eggs successfully hatched (McCullough 1999). Using the 62°F criterion, this risk model also provides the number of successful spawning days when the deposited eggs would have experienced a weekly average water temperature of 62°F or higher, at the end of their incubation.

The annual snowmelt flows significantly affect spawning and egg survival risk. Although run tail spawning deposits were common in the mainstem Clavey River, they were doubly risky. First, the low flow threshold for significant scour makes redd survival unlikely, if redds are constructed prior to the snowmelt peak. Second, the low snowmelt flows creating the spawning opportunity window force most spawning to occur late in the snowmelt recession period, which forces incubating eggs to encounter stressful temperatures close to emergence, even though the desiccation risk is very low. Nevertheless, in drier years, run tail spawning deposits at least are available, whereas other depositional features such as lee cobble deposits are higher above the thalweg and have either no windows of spawning opportunity or very short ones, and have higher risks for redd desiccation.

The highest depositional features above the thalweg were available for spawning only at high flows occurring during the rapid snowmelt recession limb. The upper point bar spawning deposit provided habitat when most other sites were flowing too fast and deep. It also had a high flow threshold for scour. The Extremely Wet runoff year (RY2005) would have mobilized the surface of this redd site, but given the variability in redd scour estimates (Table 18), a redd may still have survived. However, redds constructed on the upper point bar at the beginning of the snowmelt recession flows would be highly susceptible to desiccation.

Therefore, runoff years with less extreme flow characteristics are the best candidates for trout spawning success. The Normal and Wet runoff years provide more successful spawning habitat (Table 19) than the Extremely Wet runoff year. Of redd locations, run tail deposits were risky because the incubation period generally results in emergence under stressful temperatures (the same condition that occurs in the drier years). Lee cobble and lower point bar spawning sites are successful during high- to mid-range flows of the snowmelt recession limb, which create suitable depth and velocity. Once the eggs are deposited, eggs have time to incubate and the alevins emerge before temperatures are too hot or before desiccation.

3.4.5. Synthesizing Yellow-Legged Frog Habitat, Daily Flows, the Snowmelt Hydrograph, Scour, and Desiccation

Similar to the synthesis performed for trout life stages, yellow-legged frog requirements were examined in the context of snowmelt flow volume and timing. Expert habitat mapping allowed construction of habitat rating curves for early life stages of these frogs. Then habigraphs were created, superimposed with life stage periodicity and water temperature thresholds. Finally, through a simple spreadsheet model, the risk of egg to tadpole metamorphosis was quantified at two example depositional features; a lee deposit and a side channel.

Foothill Yellow-Legged Frog Early-Life Stage Habitat Rating Curve

Using expert habitat mapping, early-life stage habitat (i.e., habitat for oviposition, egg incubation and hatching, and tadpole metamorphosis) was identified at five flows (Figures 64 and 65); this allowed construction of a habitat rating curve (Figure 66). Foothill yellow-legged frog breeding habitat (including oviposition, or egg laying, habitat) was found everywhere in the Clavey River study reach, but not at the same time or same place. During the rising limb, peak, and fast recession limb of the snowmelt hydrograph, Cottonwood Bar provided a significant portion of total breeding habitat (Table 20), even though the bar comprised a relatively small portion of the study site's total length. During the Extremely Wet RY2005 snowmelt peak and its fast snowmelt recession limb, habitat was confined to Cottonwood Bar's side channel because flows were too fast and deep on the open bar surface. As receding snowmelt flow transitioned from the fast recession limb to the slow recession limb on Cottonwood Bar (e.g., at 184 cfs in Table 20), more breeding habitat was created over more of the bar, including the side channel, the open bar surface, and along the bar flank (Figure 64). At 57 cfs and 12 cfs, near the end of the slow snowmelt recession flows and into summer baseflows, breeding habitat was patchy along Cottonwood Bar's lower flank and both banks of the low flow main channel passing around Cottonwood Bar. As flow depths and velocities decreased with steadily decreasing snowmelt flows, the low flow main channel became more hospitable to foothill yellow-legged frog breeding habitat (Table 20).

In contrast, at the much longer boulder sub-reach during the RY2005 snowmelt peak and fast recession flows, breeding/oviposition habitat was at first scarce. The confined and narrow boulder sub-reach does not have the width to reduce flow depths and velocities at higher flows or to form large depositional features. Consequently breeding habitat does not improve until the slow snowmelt recession flows and summer baseflows begin; these flows allow habitat to increase rapidly along both banks of the boulder sub-reach's baseflow channel.

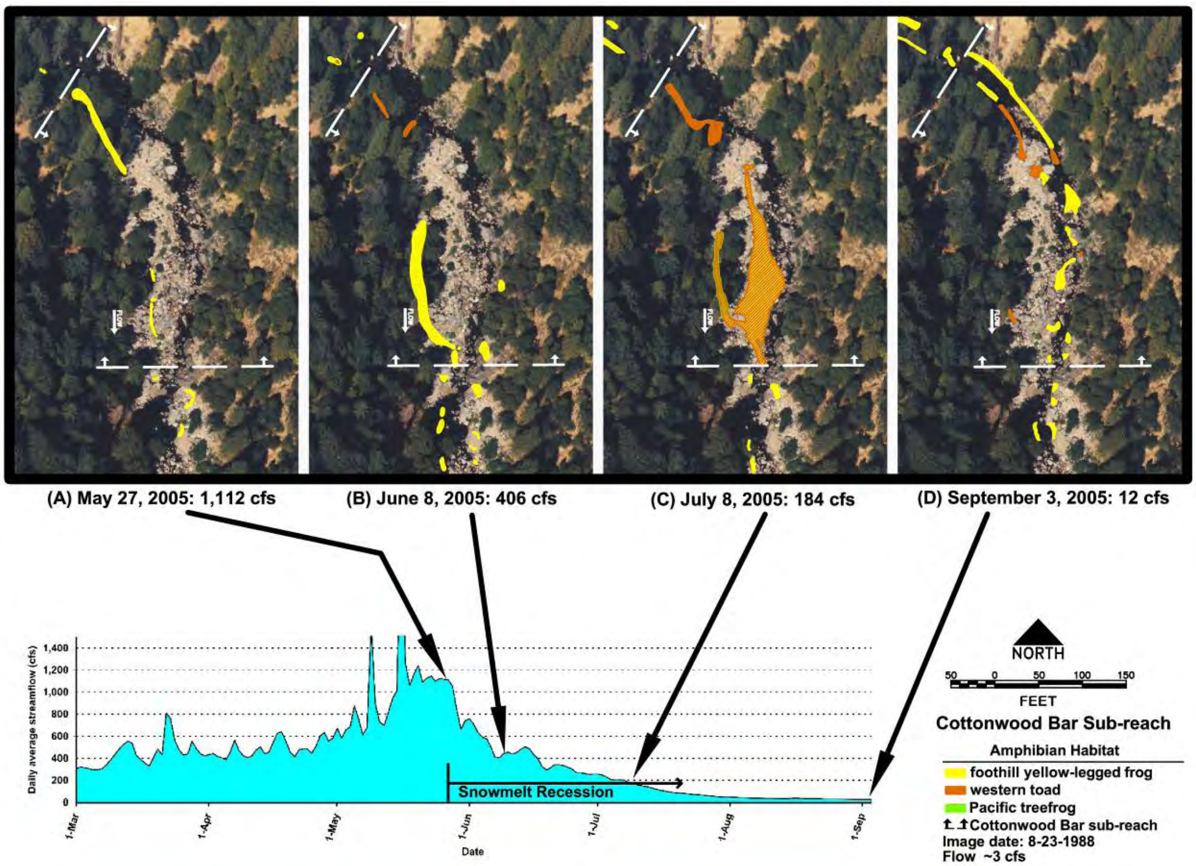


Figure 64. Foothill yellow-legged frog, western toad, and Pacific treefrog polygons from expert habitat mapping 1112 cfs, 406 cfs, 184 cfs, and 12 cfs in the Clavey River study site, Cottonwood Bar sub-reach.

For the Cherry Creek study site, the early-life stage habitat rating curve peaked twice: once at a prominent peak at 25 cfs to 40 cfs, and again at a minor peak occurring between approximately 550 cfs and 700 cfs (Figure 67). To identify peak habitat abundance, habitat mapping at additional streamflows would be needed. The Cherry Creek habitat rating curve for early-life stages of yellow-legged frogs likely dips between 700 cfs and 1200 cfs because riparian berm and sand deposition features confine streamflows before they begin to spread significantly among encroached bar features at higher streamflows.

Foothill yellow-legged frog habitat was anticipated to be greater in the Clavey River than in Cherry Creek, where woody riparian vegetation would have encroached into, and eliminated, the frogs' habitat along the channel margin. For example, the aggraded lee deposits do not provide frog habitat. Shallow and slow-moving snowmelt recession flows and summer baseflows that could have entered and inundated these lee deposits and created habitat were displaced by several feet of deposited sand. However, early-life stage total habitat area at 25 cfs was approximately 9800 ft^2 in Cherry Creek (Figure 67), and was approximately 10,000 ft^2 in the Clavey River (Figure 66), which is comparable. The study sites are of comparable length: total length of the Cherry Creek site is 2920 ft, and the Clavey River study site is 2695 ft. Their difference lies in available habitat area during the snowmelt recession flows of approximately 250 cfs, when habitat totaled roughly 2000 ft^2 at the Cherry Creek study site, but roughly 8500 ft^2 at the Clavey River study site. Woody riparian encroachment and coarse sand deposition prevent the flow from spreading throughout the channel margins and creating shallow, slow moving frog habitat. Encroached and aggraded lee deposits and many other depositional features can be seen practically everywhere within the Cherry Creek study site.

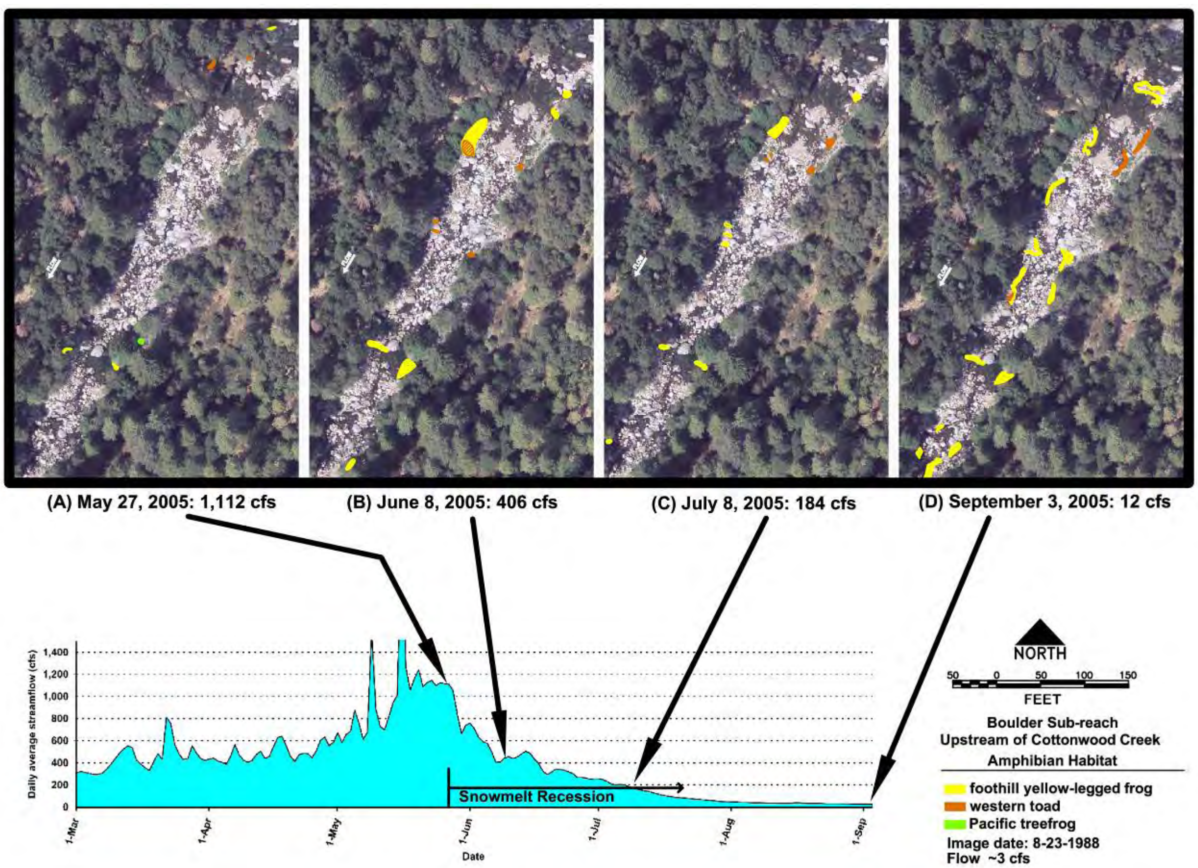


Figure 65. Foothill yellow-legged frog, western toad, and Pacific treefrog polygons from expert habitat mapping 1112 cfs, 406 cfs, 184 cfs, and 12 cfs in the Clavey River study site, boulder sub-reach.

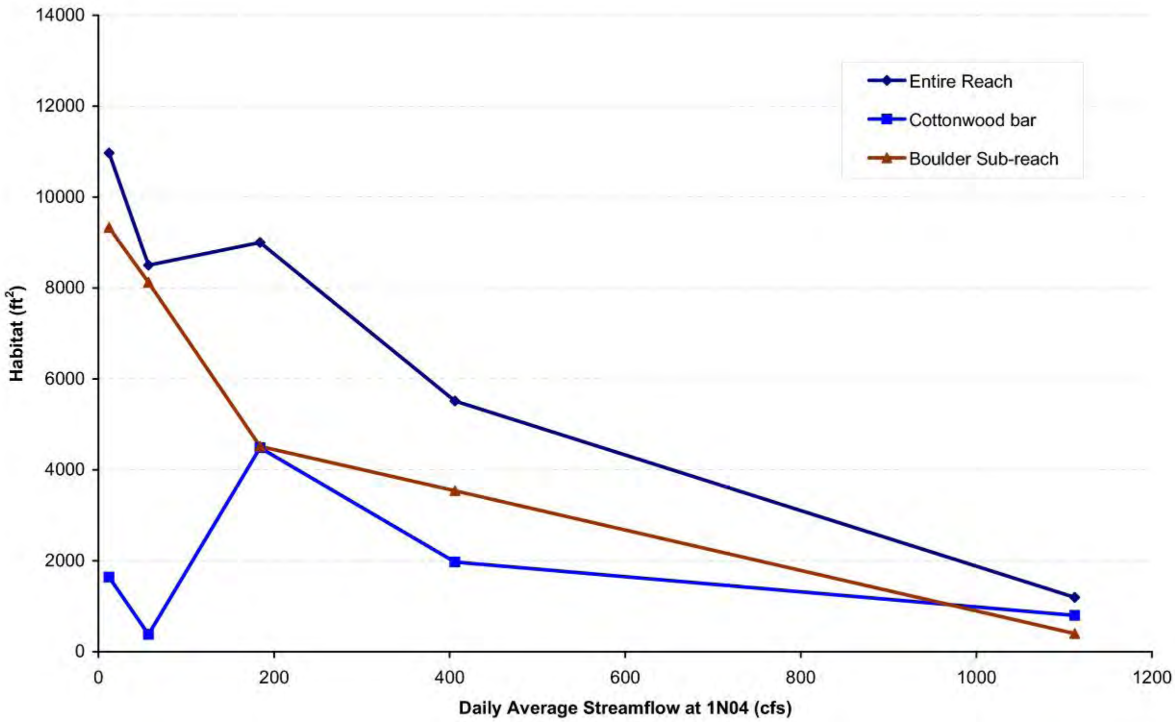


Figure 66. Foothill yellow-legged frog early-life stage habitat rating curve for the Clavey River study site.

Table 20. Foothill yellow-legged frog early-life stage mapped habitat area (ft^2) in the Clavey River study reach.

Daily average streamflow at 1N04 (cfs)	Mapped habitat area (ft^2)			Habitat density (ft^2/ft)		
	Entire study reach	Cottonwood Bar sub-reach	Boulder sub-reach	Entire study reach	Cottonwood Bar sub-reach	Boulder sub-reach
1,112	1,197	798	399	0.4	2.1	0.2
406	5,515	1,974	3,541	2.0	5.2	1.5
184	9,003	4,486	4,517	3.3	11.7	2.0
57	8,503	380	8,123	3.2	1.0	3.5
12	10,973	1,641	9,331	4.1	4.3	4.0

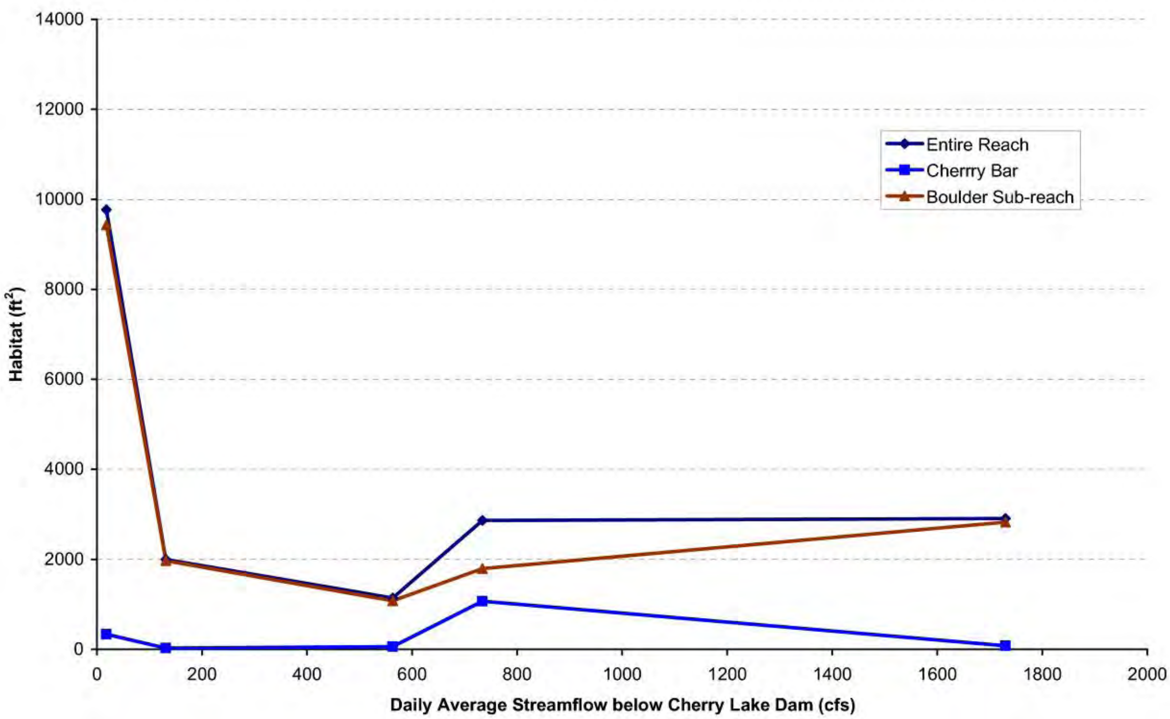


Figure 67. Foothill yellow-legged frog early-life stage habitat rating curve for the Cherry Creek study site.

Foothill Yellow-Legged Frog Early-Life Stage Habigraphs

The early-life stage habitat rating curve is simply a quantified relationship between daily average streamflow (cfs) and the amount of habitat identified during the expert habitat mapping (ft^2). But foothill yellow-legged frogs need early-life stage habitat only at certain times, and from the rating curve, one cannot estimate how much habitat is available to the frogs when they need it. To sub-set the days during RY2005 (or any other water year) when early-life stage habitat was needed, temperature thresholds that trigger the onset of breeding and that signal the end of tadpole metamorphosis were considered.

Several environmental and social cues influence breeding timing in foothill yellow-legged frogs and other amphibian species (Lind 2004). Environmental cues include water temperature, air temperature, day length, precipitation, and flow conditions; social cues include frog calling and courtship behavior. The influence of these cues has not been quantified, and no complete model is available to predict timing of breeding and other life history events based on all of these environmental and social cues. For the purposes of this project, the early life-stage window was defined as between May 1 and June 30, which coincides with reduction in flow and water temperatures between 48°F and 70°F (temperature thresholds as reported by Zweifel 1955).

Early-life stage yellow-legged frog habigraphs show the daily available habitat area during the snowmelt hydrograph, coupled with the frogs' favorable temperature range, in each sample runoff year: RY2005 (Extremely Wet), RY1973 (Wet), RY1971 (Normal), RY1968

(Dry), and RY1977 (Critically Dry) (Figures 68 to 72). Suitable water temperature was typically reached in mid- to late-May. The earliest was May 5 in RY1976 (Critically Dry) and the latest was June 11 in RY1971 (Normal). Tadpole metamorphosis is assumed to end September 28 (Table 21), but this date was determined by assuming a 90-day period between the end of oviposition and the end of metamorphosis; late oviposition would extend past the end of September (Don Ashton, pers. comm. 2006).

Inspection of the frog early-life stage habigraphs reveals the similarities and differences in where ecologically available habitat area occurs, between the Cottonwood Bar and the boulder sub-reach. During the snowmelt peak and fast recession flows of the snowmelt hydrograph, habitat area was roughly equal at the Cottonwood Bar and boulder sub-reaches, even though the boulder sub-reach is 2095 ft long and the Cottonwood Bar sub-reach is only 600 ft long. But in each runoff year, habigraphs then exhibit a sharp divergence in where habitat is generated (that is, the Cottonwood Bar and boulder sub-reach lines sharply diverge). As receding snowmelt flows reach the end of the fast recession limb and continue into the slow recession limb, Cottonwood Bar's side channel and upper surfaces are rapidly abandoned, causing habitat area to decrease sharply. The mainstem low flow channel's edge then provides most abundant habitat. The date of this sharp divergence in habitat area varies by runoff year: July 6 in Extremely Wet RY2005, June 12 in Wet RY1973, June 20 in Normal RY1971, May 18 in Dry RY1968, and May 8 in Critically Dry RY1976.

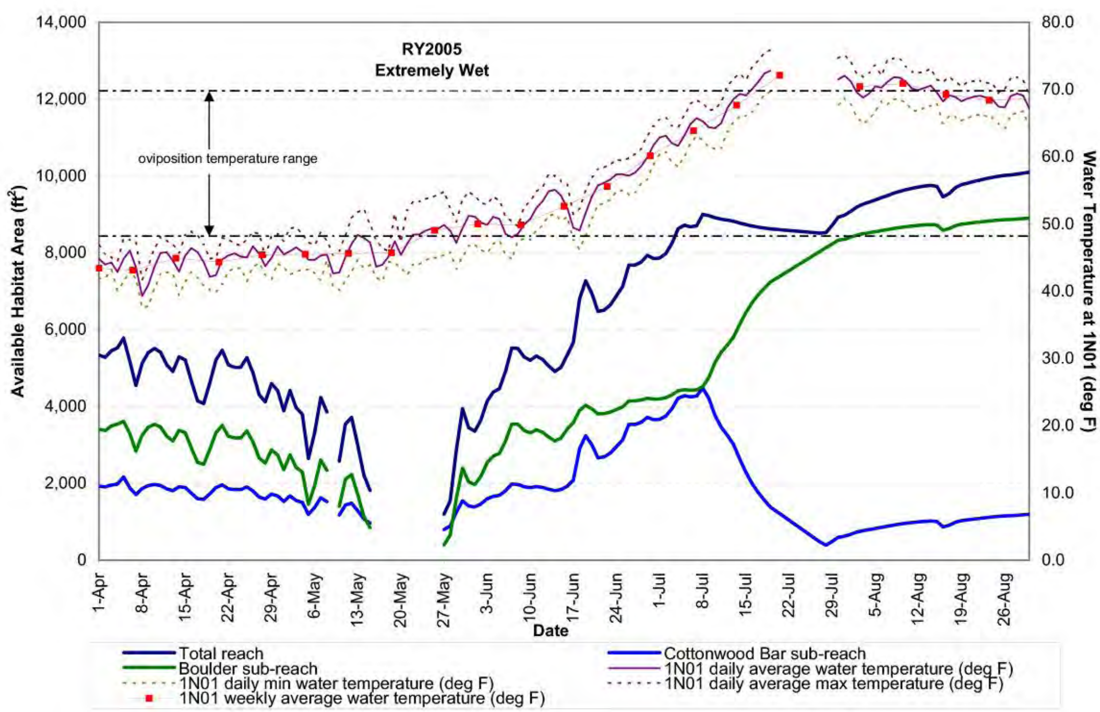


Figure 68. Habigraph for foothill yellow-legged frog early-life stage at the Clavey River study site, RY2005 (Extremely Wet).

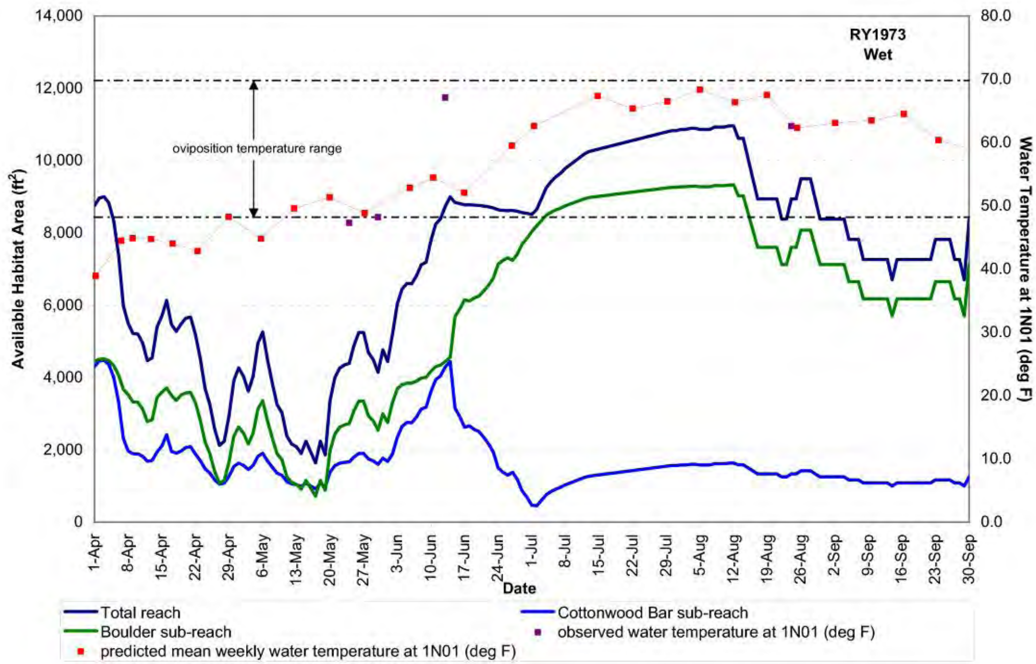


Figure 69. Habigraph for foothill yellow-legged frog early-life stage at the Clavey River study site, Y1973 (Wet).

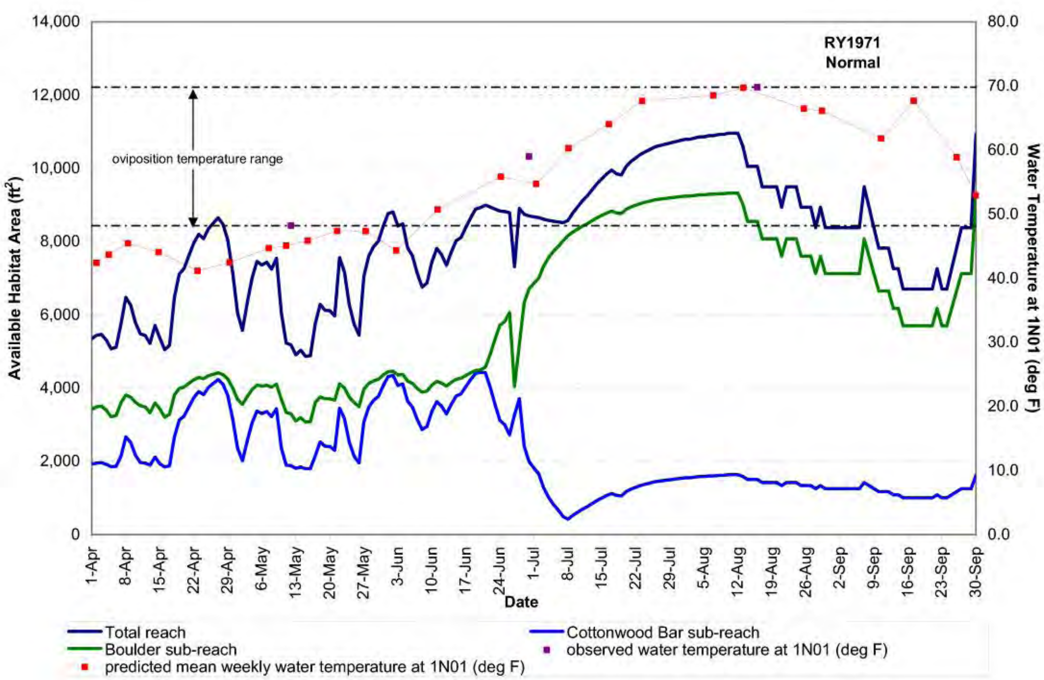


Figure 70. Habigraph for foothill yellow-legged frog early-life stage at the Clavey River study site, RY1971 (Normal).

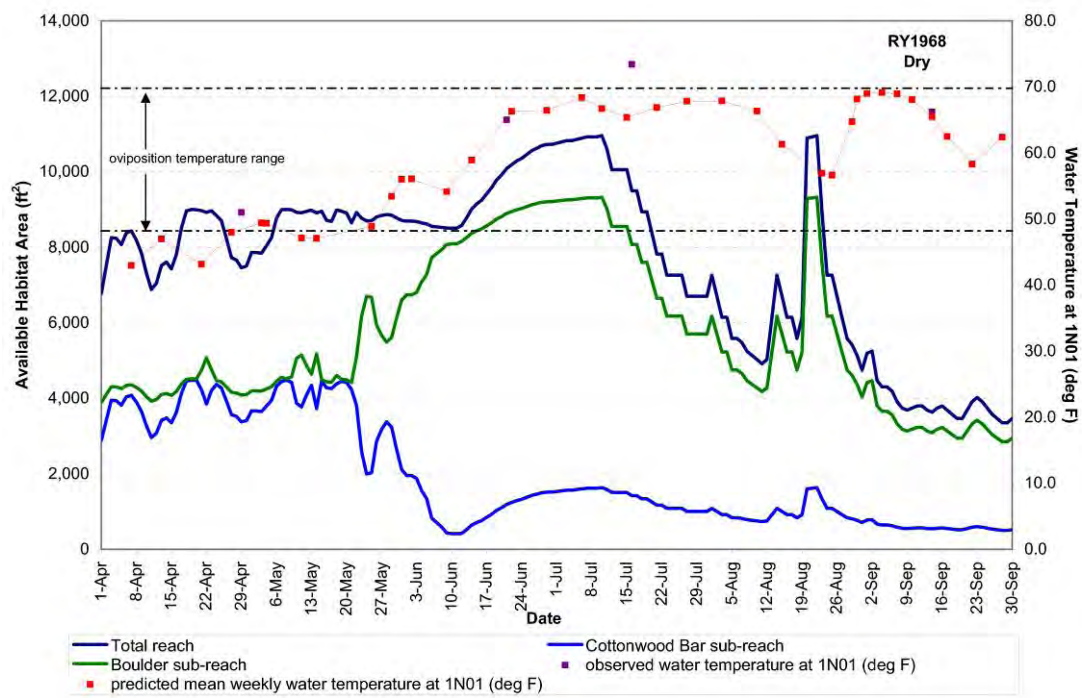


Figure 71. Habigraph for foothill yellow-legged frog early-life stage at the Clavey River study site, RY1968 (Dry).

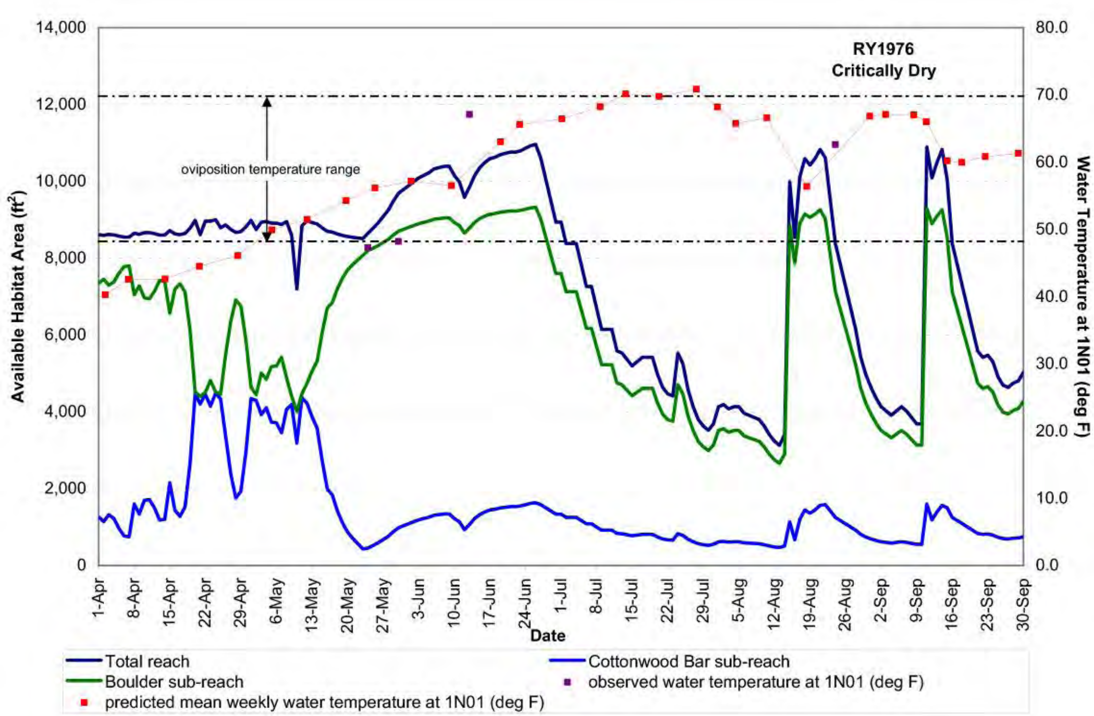


Figure 72. Habigraph for foothill yellow-legged frog early-life stage at the Clavey River study site, RY1976 (Critically Dry).

Table 21. Estimated timing of foothill yellow-legged frog life history stages for all runoff year types on the Clavey River

Runoff year	Runoff year type	Estimated early-life history timing						No. of Days	
		Oviposition		Egg hatching		Metamorphosis		Ovipo-sition	Total breeding
		begin[1]	end[2]	begin	end[3]	begin	end[4]		
2005	Extremely Wet	May 27	Jun 30	Jun 17	Jul 21	Aug 25	Sept 28	35	124
1973	Wet	May 12	Jun 30	Jun 2	Jul 21	Aug 10	Sept 28	50	139
1971	Normal	Jun 11	Jun 30	Jul 2	Jul 21	Sep 9	Sept 28	20	109
1968	Dry	May 25	Jun 30	Jun 15	Jul 21	Aug 23	Sept 28	37	126
1976	Critically Dry	May 5	Jun 30[5]	May 26	Jul 21	Aug 3	Sept 28	57	146

[1] **Dates obtained from intersection of oviposition temperature range and time on habigraphs of each runoff year.**
[2] **June 30 selected from foothill yellow-legged frog life history phenology (Figure 43).**
[3] **21 days after the end of oviposition**
[4] **90 days after the end of oviposition**
[5] **The oviposition period is unlikely to span 7 weeks; 2 to 3 weeks is typical (Don Ashton, pers. comm. 2006).**

In the dry year (RY1968), this divergence in habitat area occurs when water temperatures begin to sharply rise; in wetter runoff years (RY2005), the divergence occurs during the sharp temperature rise. Breeding behavior could be strongly influenced by this divergence period of rapid spatial and temporal change during the snowmelt recession flows, and further, when preferred oviposition temperatures occur just when habitat divergence occurs, the roles of wet versus dry years becomes apparent, in sustaining foothill yellow-legged frog populations. A large depositional feature, such as the side channel in Cottonwood Bar, may be a key contributor to early-life stage habitat in wetter years, while the low flow mainstem channel may be the key contributor in normal and drier runoff years.

Habigraphs for the snowmelt period were also constructed for the Cherry Creek study site using the five selected runoff years (Figures 73 to 77). In Extremely Wet RY2005, Cherry Creek flows fluctuated by an order of magnitude throughout the oviposition period of May 1 through June 30. Four large flow peaks occurred from May 1 through June 30. Eggs laid early May would have been scoured by the first peak. Eggs laid during the descending limb of each following peak would have been vulnerable to desiccation then scour during subsequent flow peaks. Under these conditions, all or most eggs deposited in RY2005 would likely have died. Habitat was available and nearly constant in the other four runoff years, each having a notable increase when baseflows changed on July 1. At these baseflows, habitat is confined to the baseflow channel.

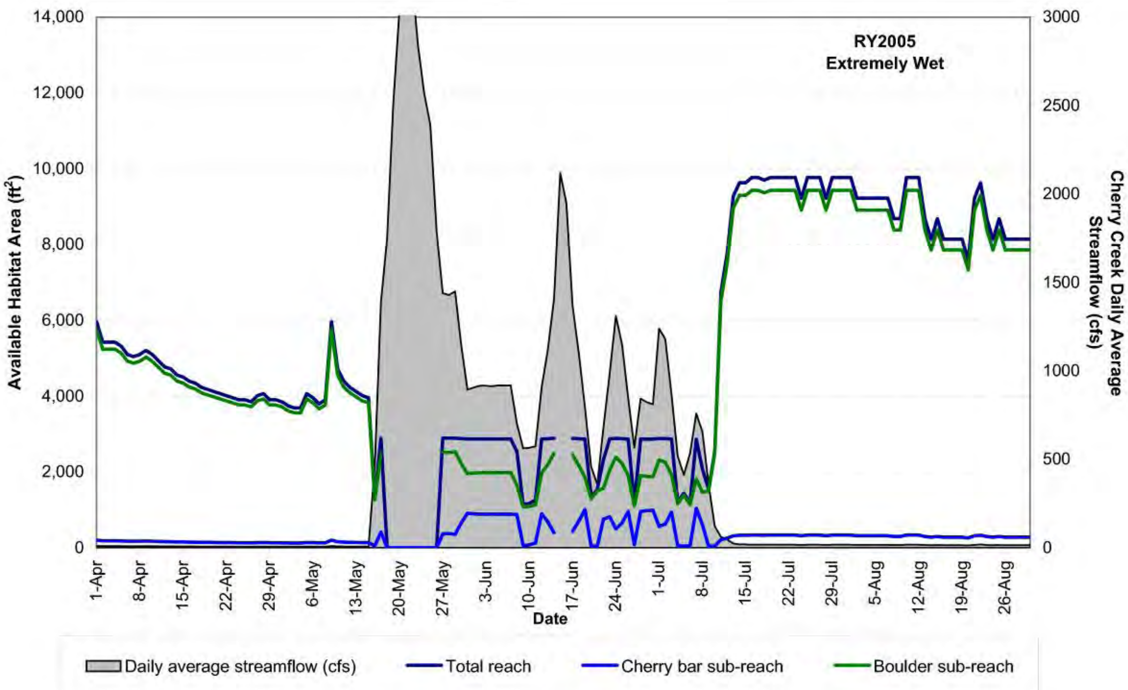


Figure 73. Habigraph for foothill yellow-legged frog early-life stage at the Cherry Creek site, RY2005 (Extremely Wet).

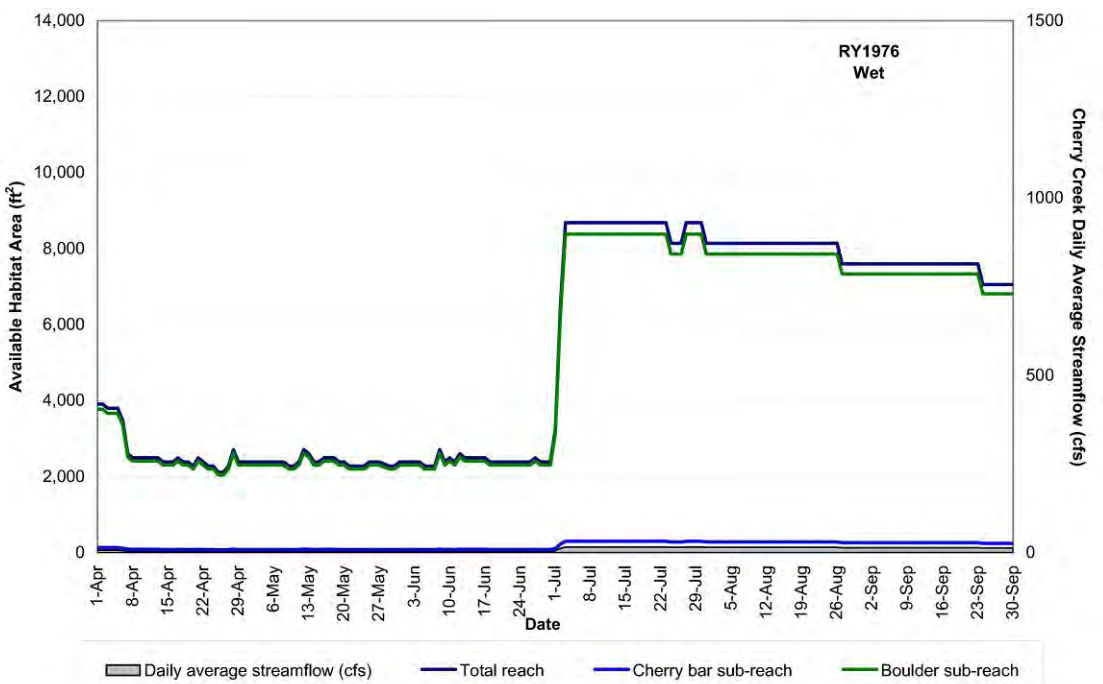


Figure 74. Habigraph for foothill yellow-legged frog early-life stage at the Cherry Creek site, RY1973 (Wet).

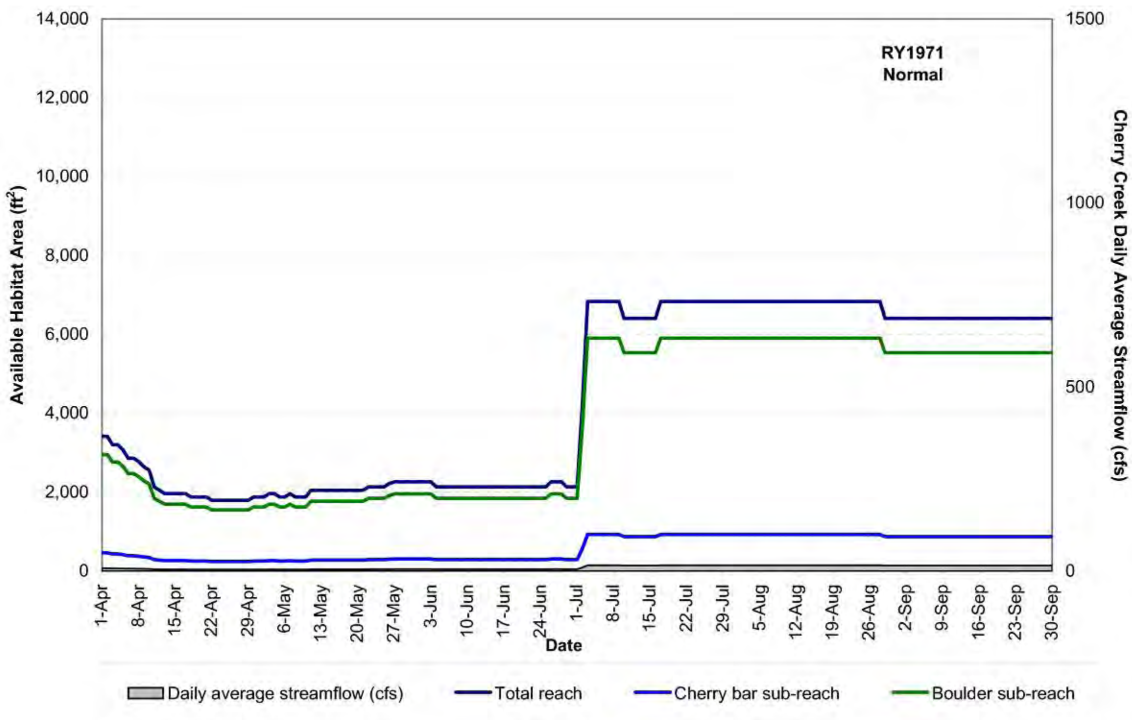


Figure 75. Habigraph for foothill yellow-legged frog early-life stage at the Cherry Creek site, RY1971 (Normal).

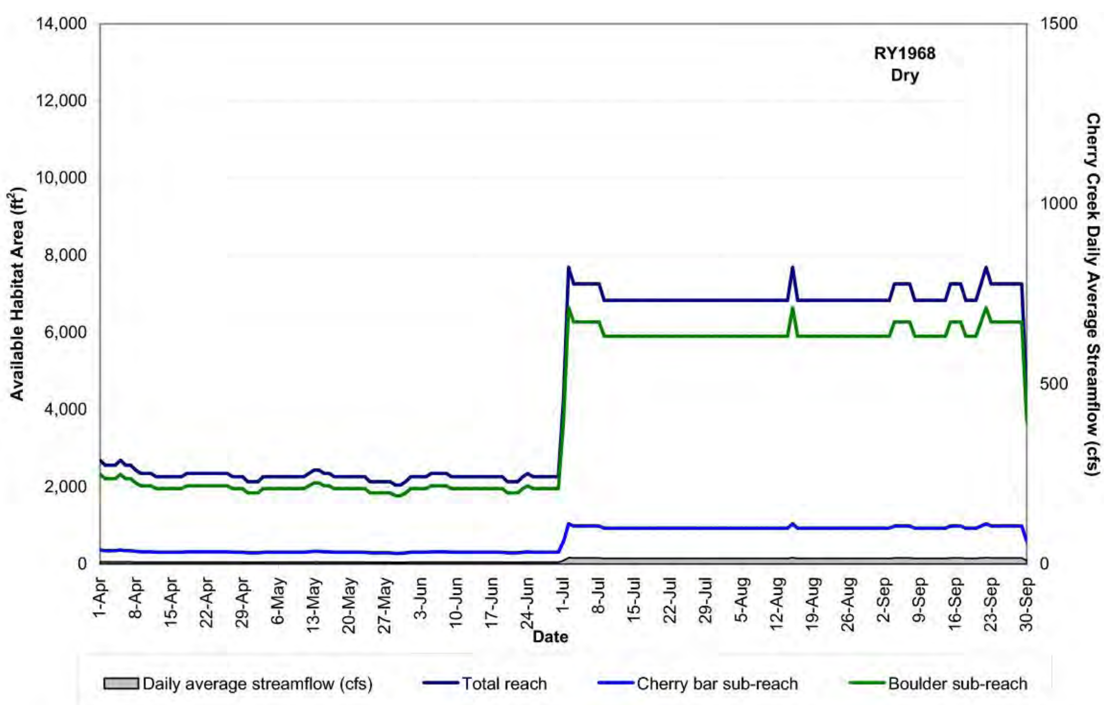


Figure 76. Habigraph for foothill yellow-legged frog early-life stage at the Cherry Creek site, RY1968 (Dry).

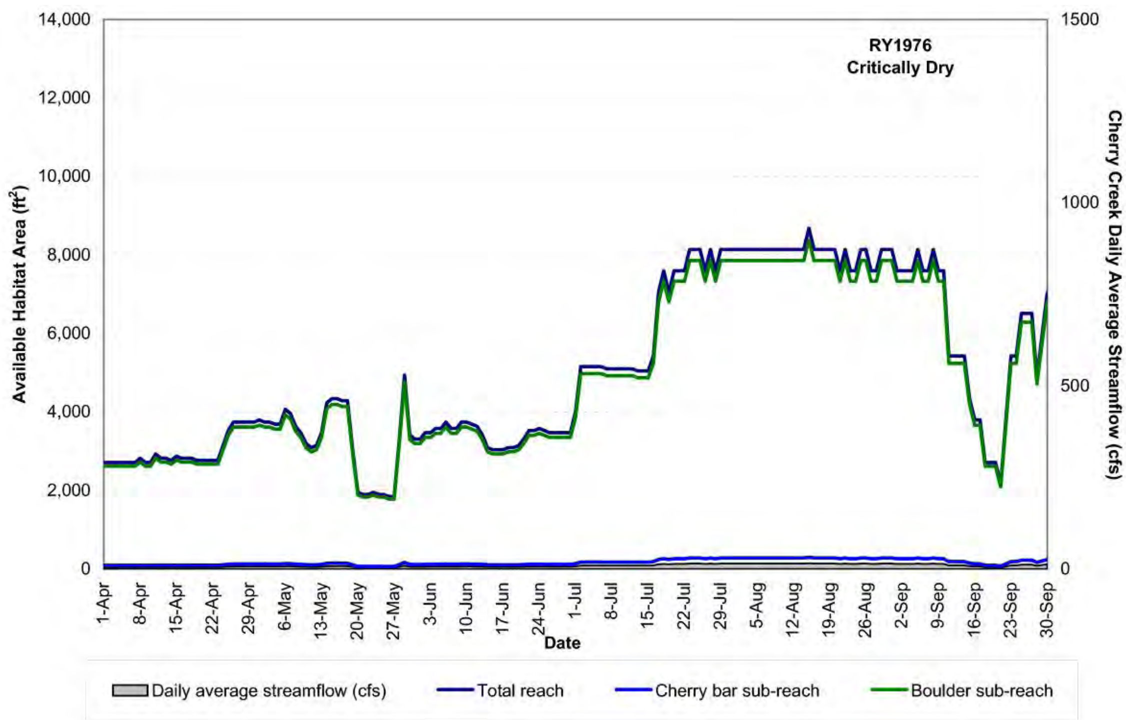


Figure 77. Habigraph for foothill yellow-legged frog early-life stage at the Cherry Creek site, RY1976 (Critically Dry).

Foothill Yellow-Legged Frog Tadpole Metamorphosis Risk in Depositional Features

Similar to trout eggs, foothill yellow-legged frog eggs that are deposited during snowmelt recession flows risk desiccation and/or scour. A simple risk assessment spreadsheet model was developed to assess whether scour or desiccation would occur at two example depositional features, during the selected runoff years. The two example depositional features selected were a lee deposit in a boulder sub-reach, and a side channel of Cottonwood Bar. Risk assessment required establishing estimated time periods for the frog's life stages (Table 21), based on reported water temperature thresholds (See the Foothill Yellow-legged frog subsection under Section 3.3.5). Considering that the start of the oviposition time period varies with each type of runoff year (e.g., May 27 though June 30 in RY2005 in Table 21), the dates for the egg hatching and metamorphosis life stages can be estimated.

Lee Deposit in Boulder Sub-Reach

At the upper end of the Clavey River study site's boulder sub-reach, mainstem channel cross section XS 35+67 lies between two closely spaced boulder ribs. Potential oviposition habitat was documented in a side-pool that had been scoured in a lee deposit, protected by a bedrock outcrop on the right bank. No habitat was available on/near XS 35+67 during peak snowmelt flows (e.g., 1112 cfs and higher), but habitat was available during fast and/or slow snowmelt recession flows (406 cfs and 184 cfs) and along the margins of the low-flow main channel during lower slow snowmelt recession flows and summer baseflow (57 cfs and 12 cfs).

At this lee deposit surveyed in cross section XS 35+67, egg desiccation was assessed using flow depths at any given streamflow computed from the cross section's rating curve. A threshold for incubation duration of 21 days was modeled using two conservative oviposition depths: 1.3 ft (maximum oviposition depth) and 0.65 ft (50% maximum oviposition depth). Therefore, eggs were assumed to have died when side-pool stage decreased below either of the two oviposition depths, within 21 days after the eggs were laid. In the spreadsheet model, successful early-life stage occurred when eggs were laid during a breeding day within the lower and upper temperature thresholds, and experienced 21 continuous days desiccation-free (Table 22). This habitat patch was hydraulically connected to the mainstem channel during summer baseflows. Therefore, eggs that were successfully hatched could grow and metamorphose as tadpoles without additional risk of desiccation.

Table 22. Modeled foothill yellow-legged frog early-life stage success (days) for a side pool in a lee deposit of the Clavey River boulder sub-reach, by runoff year.

Runoff year	Runoff year type	No. of successful early-life stage days
2005	Extremely Wet	33
1973	Wet	35
1971	Normal	20
1968	Dry	10
1976	Critically Dry	13

<u>Cottonwood Bar's Side Channel</u>

Surface flow into Cottonwood Bar's side channel and open point bar surface is controlled by the bar head and side channel inlet (near cross section XS 16+33) (Figure 78). Flow begins inundating the point bar surface at 160 cfs and begins flowing into the side channel at 210 cfs. Flow conditions remain suitable for breeding in the side channel from 210 cfs up to 1100 cfs. Below 160 cfs, isolated pools within the side channel continued providing tadpole rearing habitat at least through the final RY2005 habitat survey of September 3, 2005, at 12 cfs.

Once mainstem streamflows drop below approximately 210 cfs, tadpoles rearing in isolated pools of the side channel lose the option of swimming to the main channel and risk desiccation by late summer or early fall before metamorphosis. At this side channel, tadpole desiccation risk was modeled by assuming that tadpoles can rear in side channel pools until

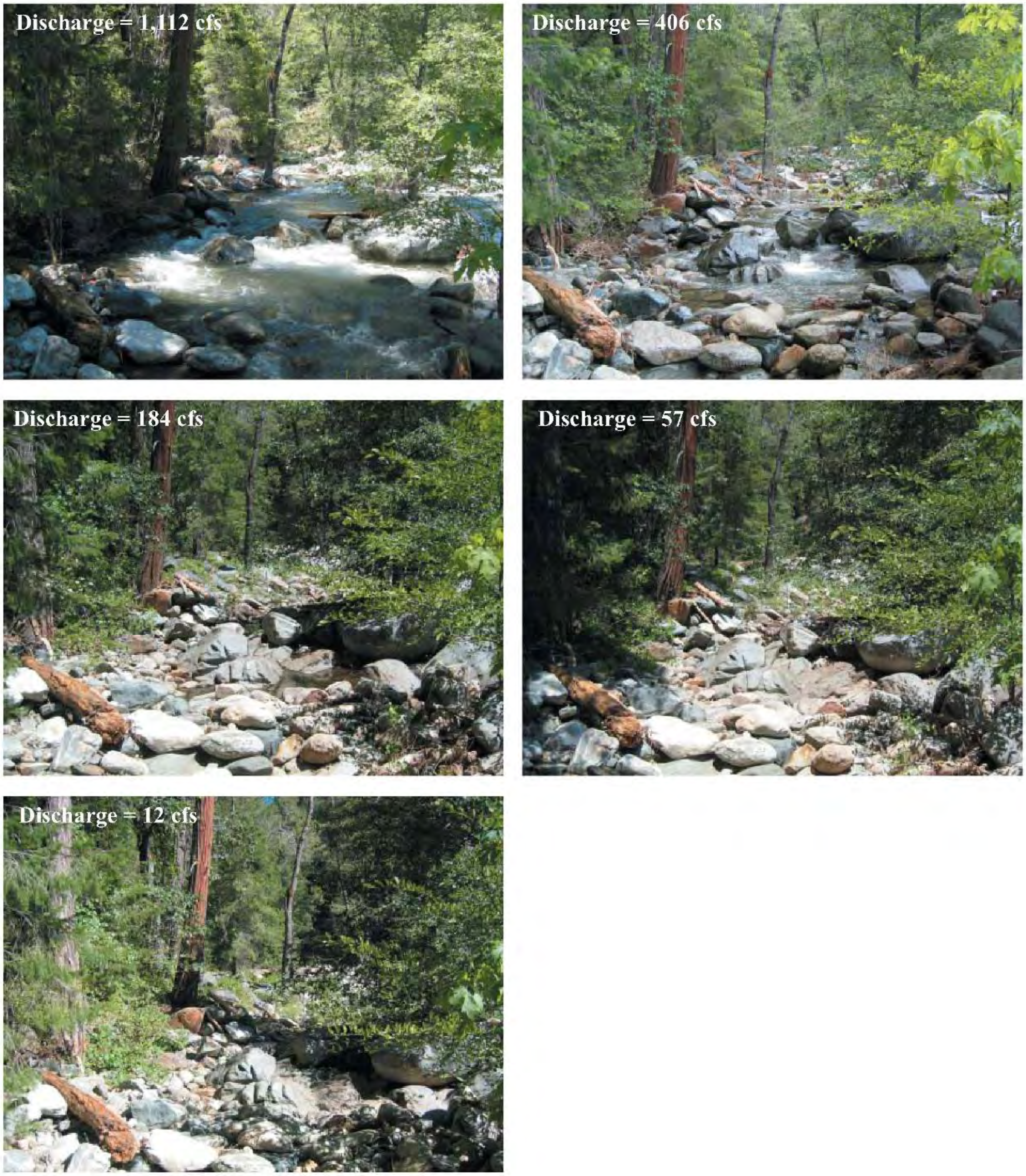


Figure 78. Cottonwood Bar side channel at mainstem streamflows of 1112, 406, 184, 57, and 12 cfs; photos taken looking upstream.

mainstem flow decreases below 12 cfs (although side-channel habitat quality was low and quality was very marginal) in any runoff year. Each of the five sample runoff years was modeled to estimate the number of successful early-life stage days (Table 23).

Table 23. Modeled foothill yellow-legged frog early-life stage success (days) for the Clavey River's Cottonwood Bar side channel, by runoff year.

Runoff year	Runoff year type	No. of successful early-life stage days
2005	Extremely Wet	36
1973	Wet	50
1971	Normal	0
1968	Dry	0
1976	Critically Dry	0

The best strategy for early-life stage success appears to be early metamorphosis, which allows the longest rearing season possible to prepare for the upcoming winter. Wet and Dry/Critically Dry runoff years provide these best habitat conditions: long oviposition window, sufficient available habitat area, and relatively early onset of metamorphosis. In a Wet runoff year, Cottonwood Bar provides approximately half of the available habitat area until flows decline below the snowmelt recession node (Section 3.1.3). Once flows decrease below the recession node, habitat area at Cottonwood Bar declines until the end of the breeding window. Only in wetter years can eggs laid in the Cottonwood Bar side channel complete metamorphosis (Table 23).

3.4.6. Synthesizing Western Toad Habitat, Daily Flows, the Snowmelt Hydrograph, Scour, and Desiccation

Similar to the synthesis performed for yellow-legged frog, life stage requirements for the western toad were examined in the context of snowmelt flow volume and timing. Expert habitat mapping allowed construction of habitat rating curves for early-life stages of these toads. Then, habigraphs were created for each sample runoff year, superimposed with water temperature thresholds and life stage periodicities.

Western Toad Early-life Stage Habitat Rating Curve

Western toad breeding habitat occurs throughout the Clavey River study reach, depending on streamflow conditions (Figures 64 and 65). For flows occurring during the 2005 habitat mapping, Cottonwood Bar was inundated at 184 cfs and breeding habitat area peaked at 6354 ft^2; along the channel margins of the boulder sub-reach and the bar's low flow channel, less habitat (2465 ft^2) was available in shallow, vegetated backwaters and isolated pools at 12 cfs (Figure 79 and Table 24). Breeding habitat in the boulder sub-reach occurred in vegetated side pools, low-flow side channels, and along the channel margin (Figure 65). In the boulder sub-reach, breeding habitat area increased slightly as flow dropped from 1112 cfs to 406 cfs, then it remained relatively constant from 406 cfs to 57 cfs. As flow

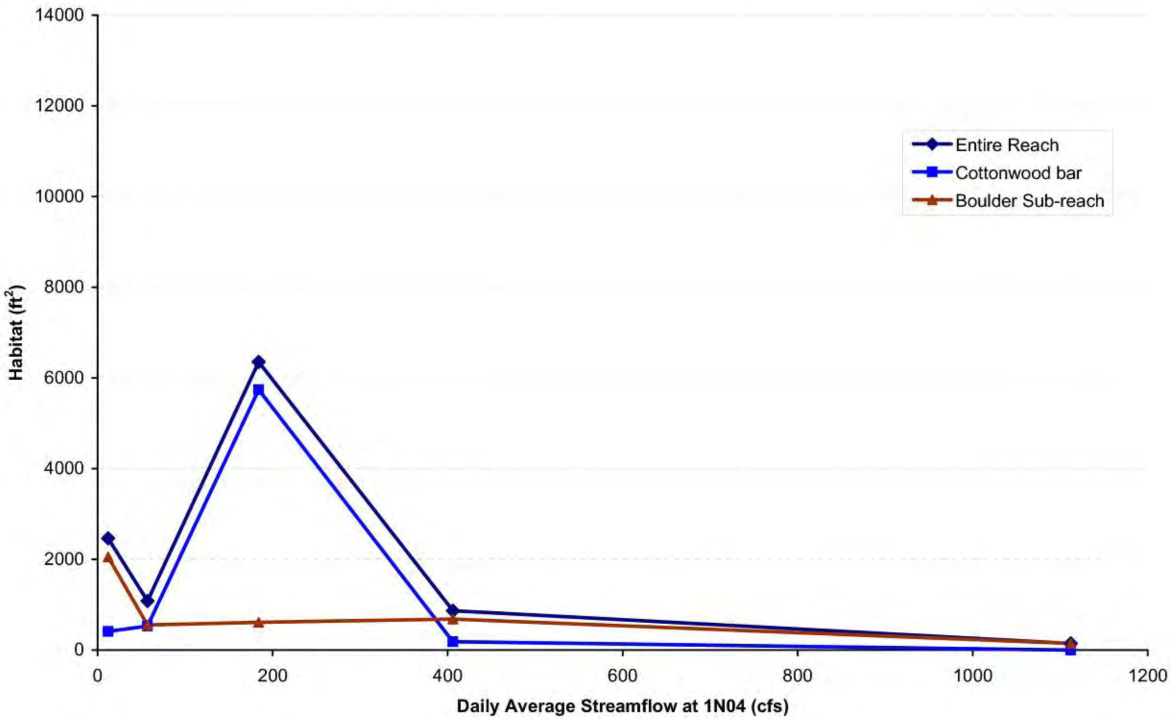


Figure 79. Western toad early-life stage habitat rating curve for the Clavey River study site.

decreased from 57 cfs to 12 cfs, mapped habitat area increased by 370%. In the boulder sub-reach for all flows mapped, habitat density ranged from 0.1 to 0.9 ft^2/ft (Table 24).

In the Cottonwood Bar sub-reach, mapped habitat area peaked at 184 cfs (5,743 ft^2) as the bar surface was inundated (Table 24). At this snowmelt recession flow, the right-bank side channel and numerous vegetated patches on the bar surface provided suitable breeding habitat (Figure 64). At 406 cfs, habitat was limited to a shallow, vegetated area at the upstream end of the bar. No habitat was available at 1112 cfs. As flow decreased to below the elevation of the bar surface (57 cfs and 12 cfs), habitat area was reduced to isolated pools in the side channel and on the bar surface, and in inundated vegetation on the channel margins. For the extreme high and low flows mapped, habitat density in the Cottonwood Bar sub-reach was similar to the boulder sub-reach (Table 24). However, at moderate flows,

Table 24. Western toad breeding mapped habitat area in Clavey River study reach.

Daily avg. flow at 1N04 (cfs)	Mapped habitat area (ft^2)			Habitat density (ft^2/ft)		
	Entire study reach	Cottonwood Bar sub-reach	Boulder sub-reach	Entire study reach	Cottonwood Bar sub-reach	Boulder sub-reach
1,112	146	0	146	0.1	0.0	0.1
406	867	183	684	0.3	0.5	0.3
184	6,354	5,743	611	2.4	15.0	0.3
57	1,084	530	553	0.4	1.4	0.2
12	2,465	412	2,053	0.9	1.1	0.9

Cottonwood Bar habitat density greatly exceeded that of the boulder sub-reach (at 57 cfs, habitat density at the Cottonwood Bar sub-reach was 1.4 ft^2/ft, or 7 times greater than that at the boulder sub-reach). At 184 cfs, when the bar surface and side channel were inundated, habitat density at Cottonwood Bar was 15 ft^2/ft, or 50 times greater than in the boulder sub-reach.

For the western toad, the Cherry Creek and Clavey River habitat rating curves (Figures 79 and 80, respectively) are similar in shape, although Cherry Creek habitat area is roughly half that of the Clavey River. The Cherry Creek boulder sub-reach generates habitat only when flows begin to overtop the channel margin and riparian berms and fills isolated pockets. The Clavey River boulder sub-reach generates habitat when flow simply migrates up the bank among unencroached boulders.

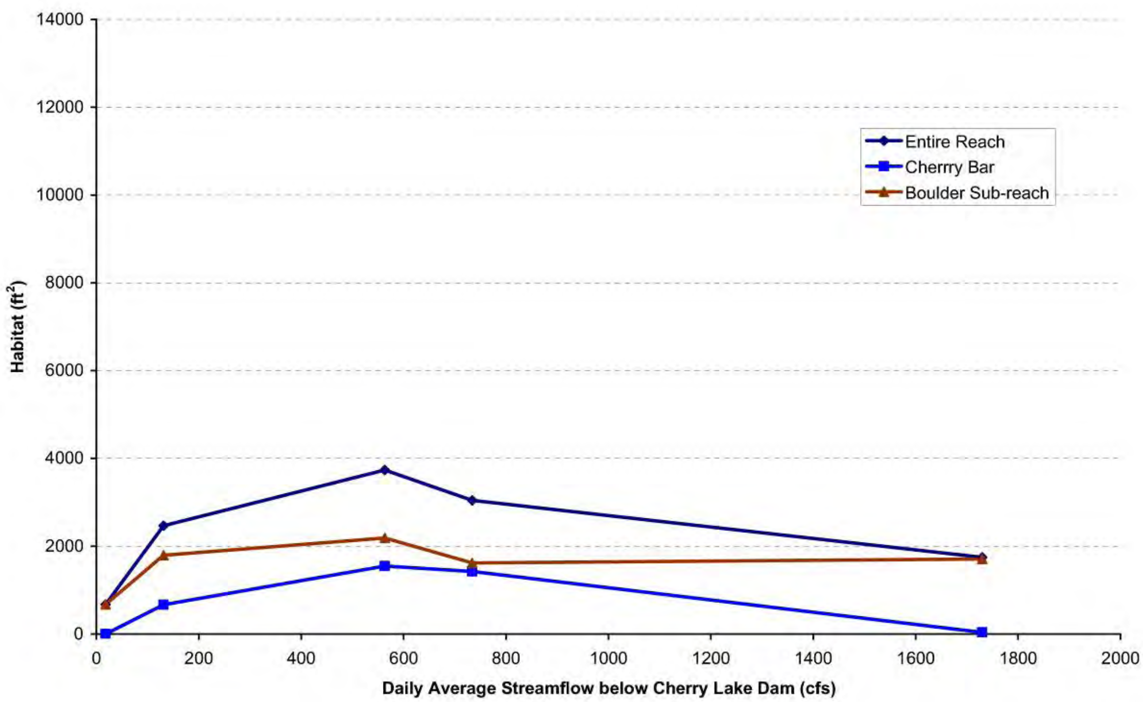


Figure 80. Western toad early-life stage habitat rating curve for the Cherry Creek study site.

Western Toad Habigraphs

In the Clavey River Cottonwood Bar and boulder sub-reaches, ecologically available breeding habitat was present in all habigraphs analyzed (Figures 81 to 85). For this analysis, the western toad oviposition window was defined as April 1 through July 31, and the minimum temperature at which oviposition could begin was defined as 40°F. In all runoff

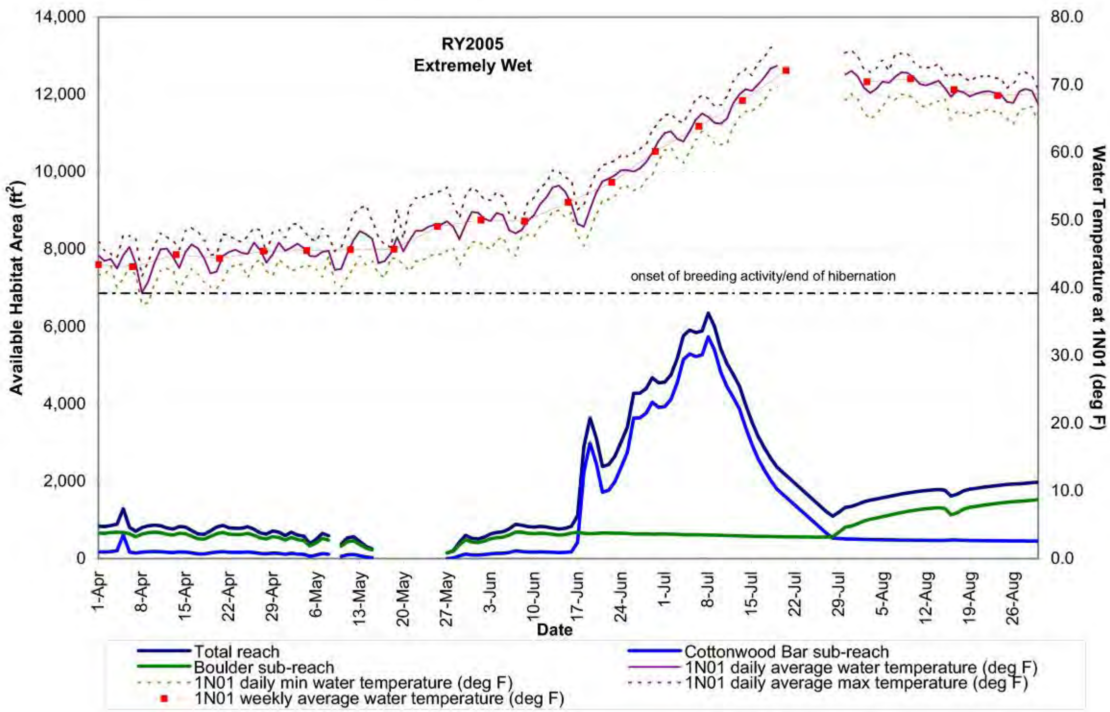


Figure 81. Habigraph for western toad early-life stage on the Clavey River, RY2005 (Extremely Wet).

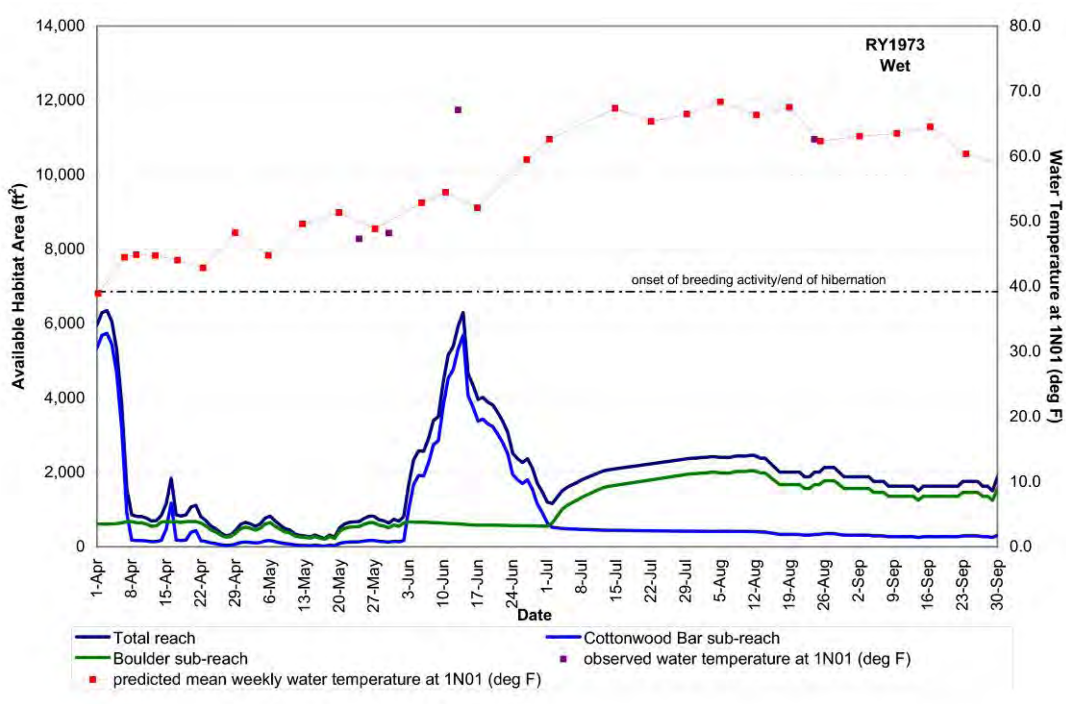


Figure 82. Habigraph for western toad early-life stage on the Clavey River, RY1973 (Wet).

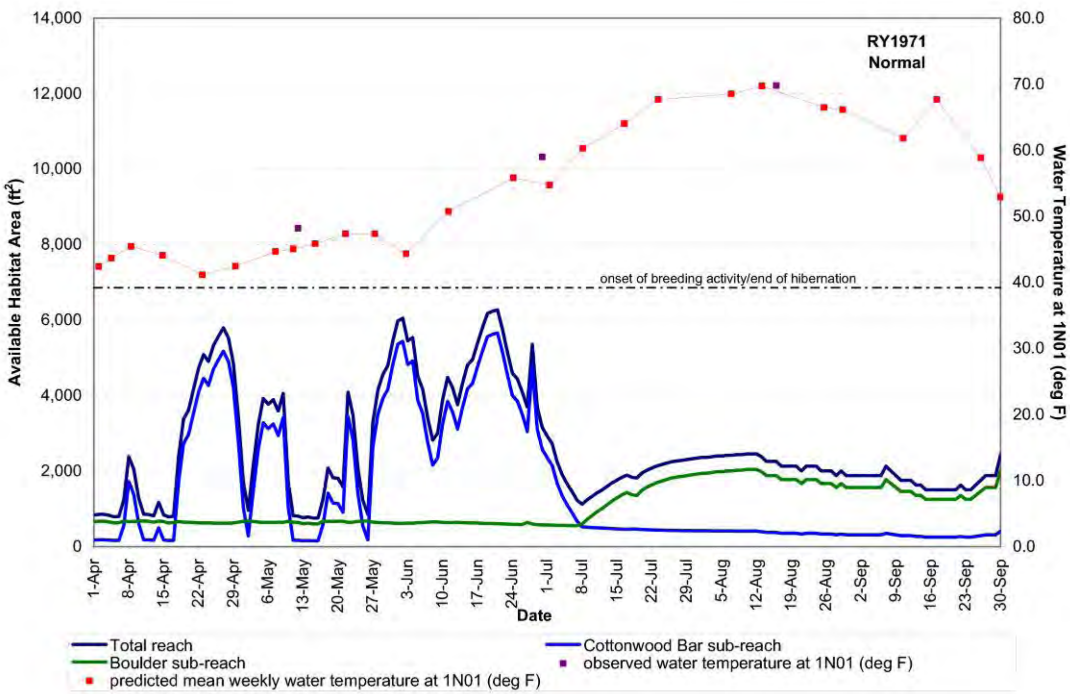


Figure 83. Habigraph for western toad early-life stage on the Clavey River, RY1971 (Normal).

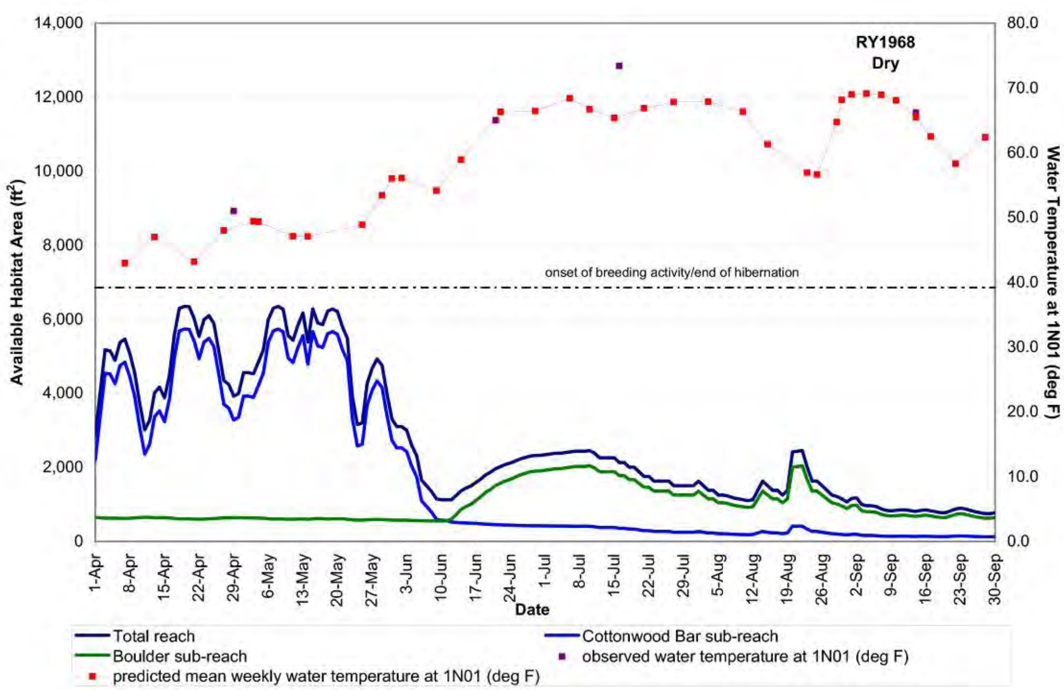


Figure 84. Habigraph for western toad early-life stage on the Clavey River, RY1968 (Dry).

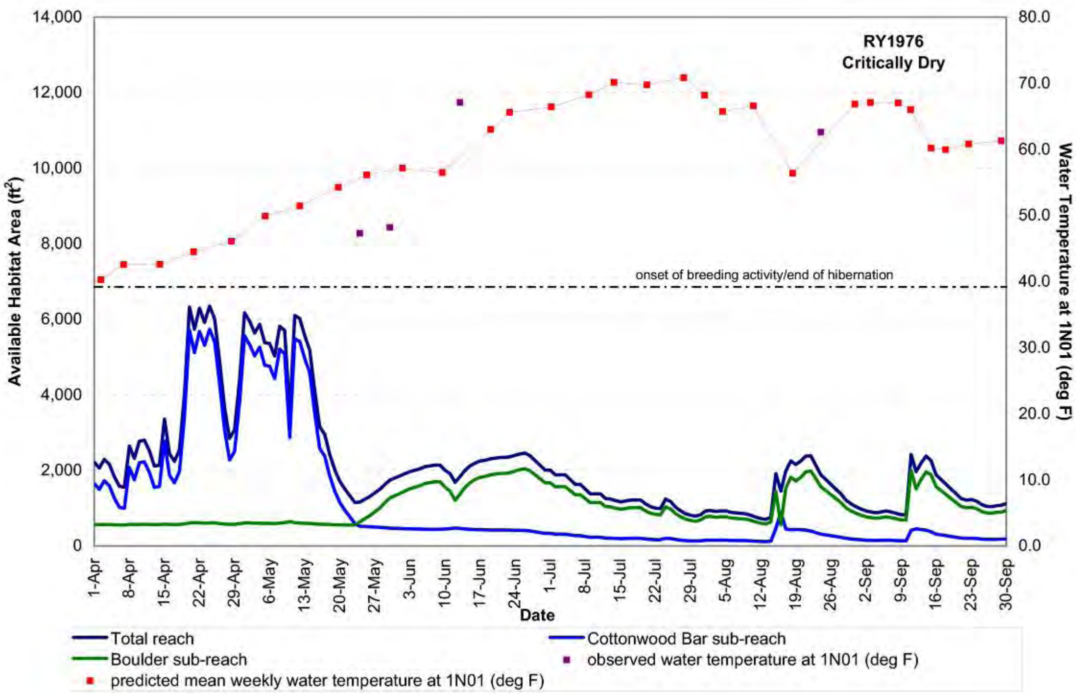


Figure 85. Habigraph for western toad early-life stage on the Clavey River, RY1976 (Critically Dry).

years analyzed, suitable breeding temperature was reached before April 1, so water temperature is not a primary factor driving the onset of breeding activity. Instead, life history timing was based on western toad life history phenology (Figure 44), time required for eggs to hatch (seven days), and time required for eggs to metamorphose (63 days) (Table 25). April 1 was assumed to be the beginning of the oviposition period for Normal, Dry, and Critically Dry runoff years.

Habitat shifts from the Cottonwood Bar sub-reach to the boulder sub-reach, depending on flow (as shown when available habitat for the Cottonwood Bar and boulder sub-reach diverge, Figures 81 to 85). Ecologically available habitat is generally higher at Cottonwood Bar during high snowmelt recession flows; ecologically available habitat is higher in the boulder sub-reach during low snowmelt and summer baseflows. Larger individuals, hatching earlier with more time to grow, have a better chance of over-winter survival.

Table 25. Estimated timing of western toad life history stages in the Clavey River, by runoff years.

Runoff year	Runoff year type	Estimated life history timing						Days ovipo-sition
		Oviposition		Egg hatching		Metamorphosis		
		Begin	End[1]	Begin[2]	End[3]	Begin[4]	End[5]	
2005	Extremely Wet	Jun 16[6]	Jul 31	Jun 23	Aug 7	Aug 18	Oct 2	45
1973	Wet	Jun 2[7]	Jul 31	Jun 9	Aug 7	Aug 4	Oct 2	59
1971	Normal	Apr 1	Jul 31	Apr 8	Aug 7	Jun 3	Oct 2	121
1968	Dry	Apr 1	Jul 31	Apr 8	Aug 7	Jun 3	Oct 2	121
1976	Critically Dry	Apr 1	Jul 31	Apr 8	Aug 7	Jun 3	Oct 2	121

[1] **End of breeding window (Figure 44)**
[2] **7 days after oviposition begins**
[3] **7 days after oviposition ends**
[4] **63 days after oviposition begins**
[5] **63 days after oviposition ends**
[6] **Date of increase of early-life stage available habitat (Figure 81)**
[7] **Date of increase of early-life stage available habitat (Figure 82)**

3.4.7. Synthesizing Pacific Tree Frog Habitat, Daily Flows, the Snowmelt Hydrograph, Scour, and Desiccation

Pacific Treefrog Habitat Rating Curve

Compared to other amphibian species of concern, Pacific treefrog breeding, oviposition, and tadpole habitat was limited throughout the study reach (Figures 64 and 65). For streamflows mapped in RY2005 on Cottonwood Bar, mapped habitat area peaked at 184 cfs (532 ft^2) as the bar was inundated (Figure 86). When flows decreased below 184 cfs on Cottonwood Bar, habitat became available, then persisted through the mapping surveys that ended September 3, 2005 (Figure 64). Habitat occurred on the bar's right-bank side channel. As pools remaining in the side channel shrank over the summer, mapped habitat area decreased. No habitat was available at 406 cfs and 1112 cfs.

In the boulder sub-reach at 406 and 1100 cfs, habitat was limited to the margins of a single large side-pool near the Cottonwood Creek confluence. At 12 cfs, mapped habitat area in the boulder sub-reach was 1179 ft^2, occurring in shallow backwaters among boulders and isolated side-pools.

At 12 cfs, total Pacific treefrog habitat was 1213 ft^2, occurring primarily in vegetated side-pools, low flow side channels, and along the channel margin in isolated pockets among boulders.

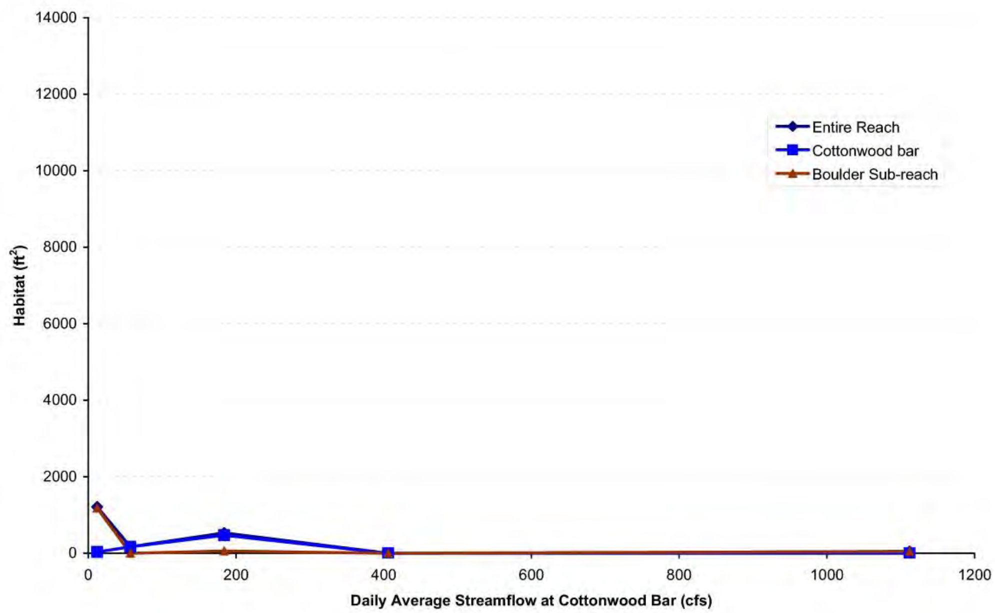


Figure 86. Pacific treefrog early-life stage habitat rating curve for the Clavey River study site.

The shapes of the Pacific treefrog habitat rating curves of the Clavey River and Cherry Creek are not similar (Figures 86 and 87, respectively). On Cherry Creek during low summer baseflows, the channel margins have been encroached by riparian vegetation, which eliminates pockets of favorable habitat. On the boulder sub-reach of Cherry Creek, when higher flows (> 200 cfs) overtop the channel margin and riparian berm, pockets of favorable habitat are generated.

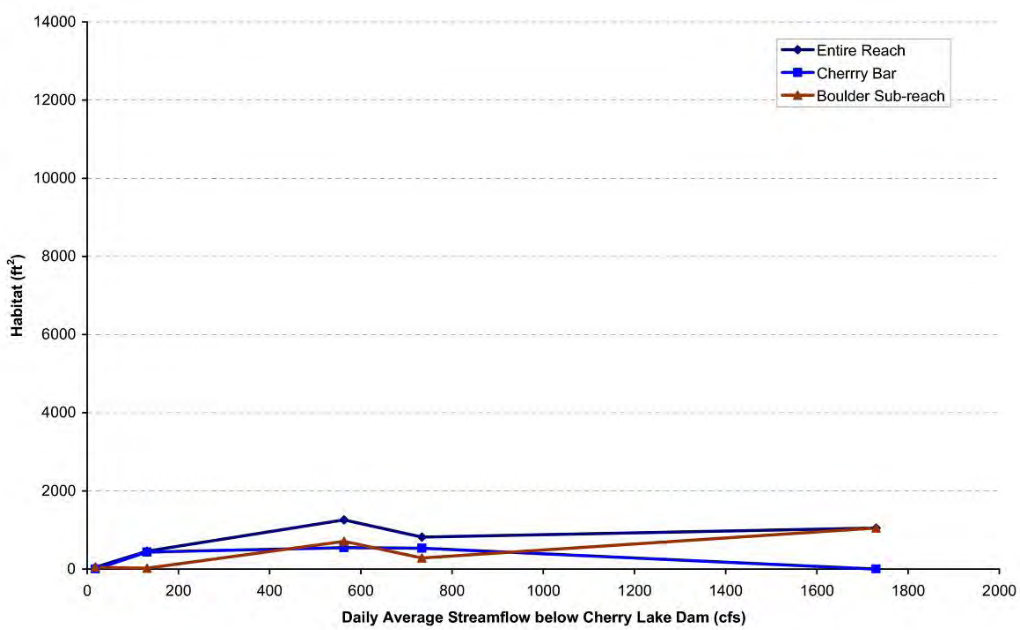


Figure 87. Pacific treefrog early-life stage habitat rating curve for the Cherry Creek study site.

Pacific Treefrog Habigraphs

Pacific treefrog habitat was sparse in Cottonwood Bar and the boulder sub-reaches in all runoff years analyzed (Figures 88 to 92). For the selected runoff years, and assuming suitable breeding temperatures range as low as 32°F to as high as even 40°F, water temperature is not a primary factor that triggers breeding activity. The estimated timing for oviposition, egg hatching, and metamorphosis did change by runoff year (Table 26).

For the five selected runoff years, the Pacific treefrog habigraphs were not markedly different. In part, ecologically available habitat was always low everywhere. But similar to findings of the western toad and the yellow-legged frog, large depositional features provided habitat in higher snowmelt streamflows, while the boulder sub-reach provided some habitat at low snowmelt flows and summer baseflows. In the Cottonwood Bar side channel in wetter years, ecologically available habitat was low at the end of the slow snowmelt recession period, but habitat quality remained high. In August 1993, the open surface of Cottonwood Bar provided numerous depressions filled with standing water that would have provided Pacific treefrog habitat. The January 1997 flood deposited boulders and large cobbles throughout the bar's open surface and eliminated these depression and scour holes.

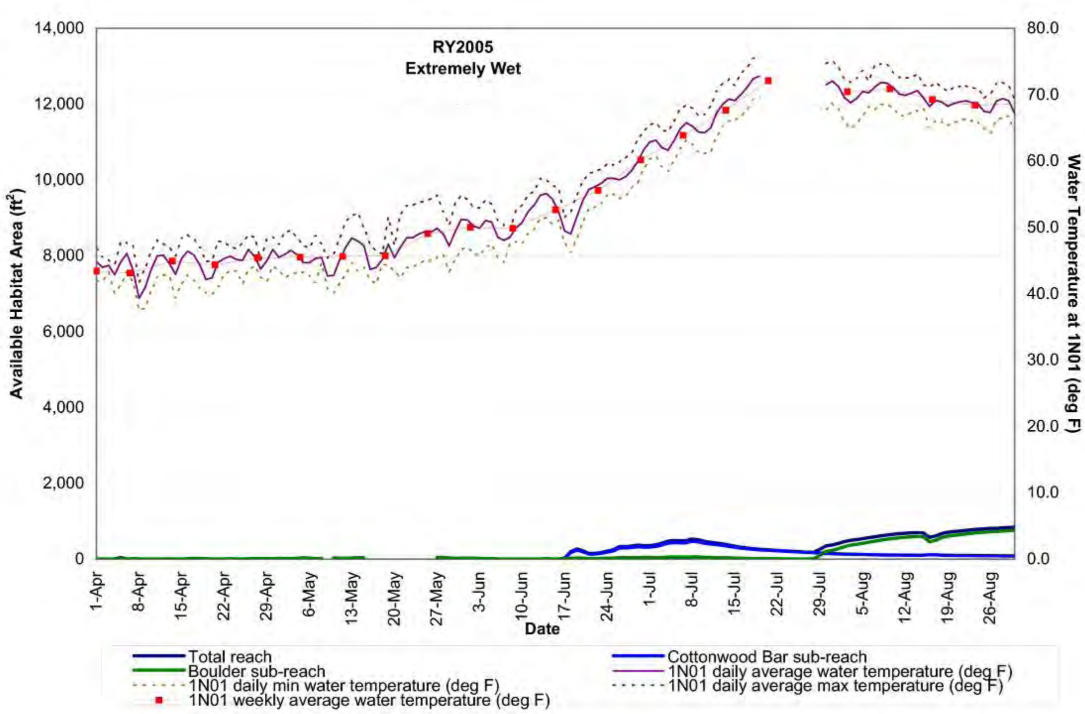


Figure 88. Habigraph for Pacific treefrog early-life stage on the Clavey River, RY2005 (Extremely Wet).

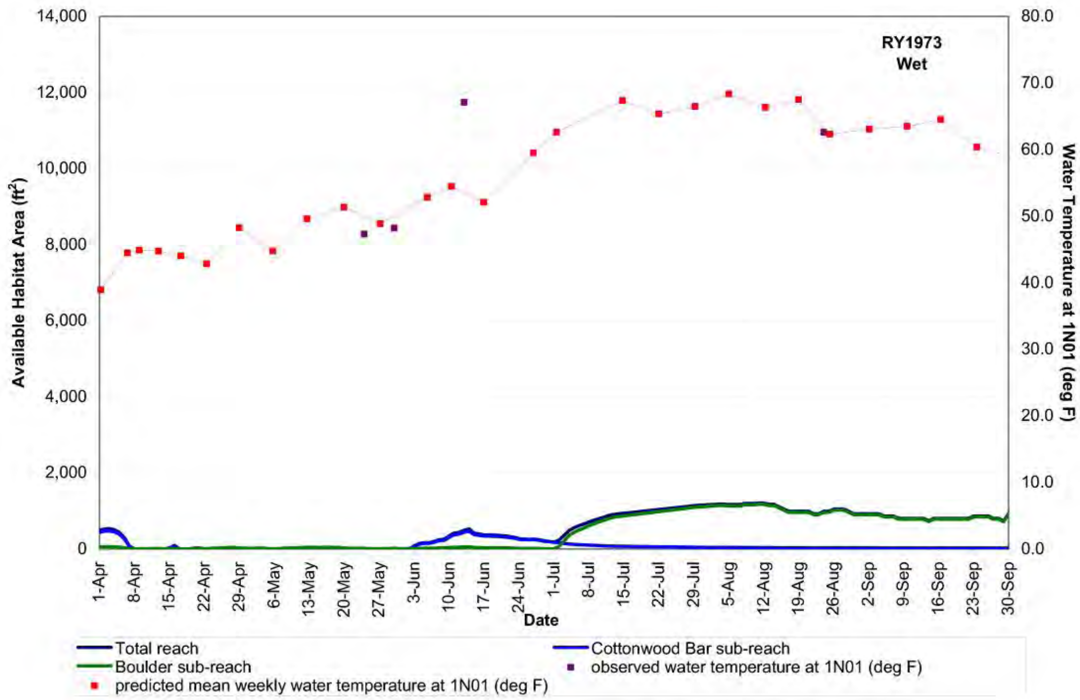


Figure 89. Habigraph for Pacific treefrog early-life stage on the Clavey River, RY1973 (Wet).

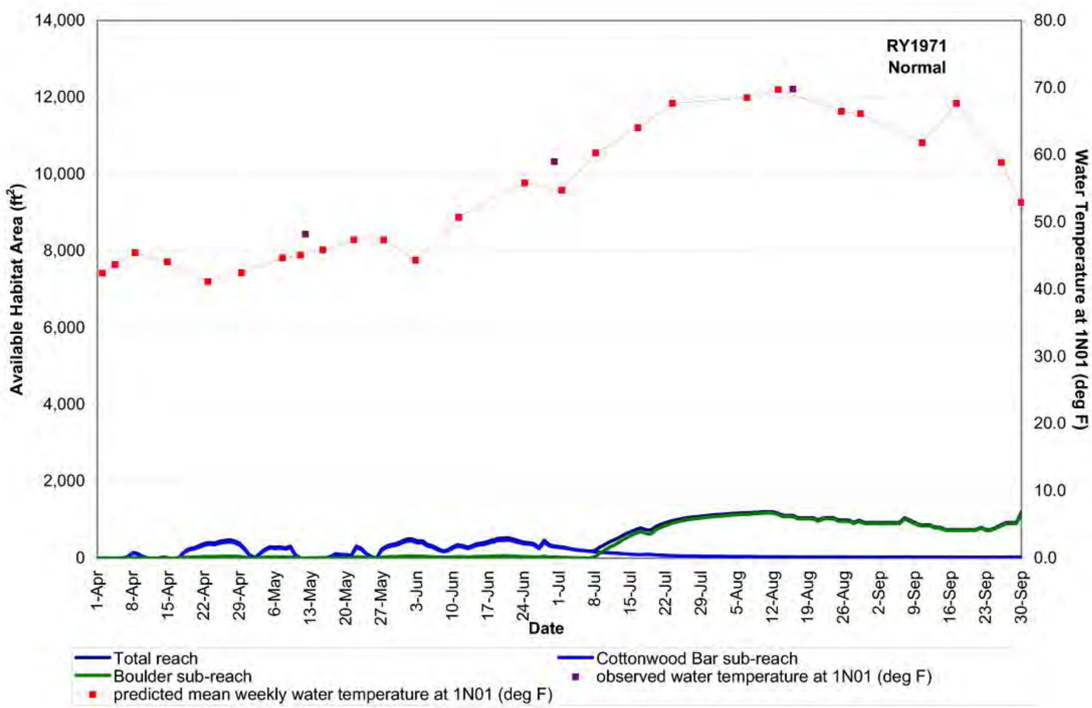


Figure 90. Habigraph for Pacific treefrog early-life stage on the Clavey River, RY1971 (Normal).

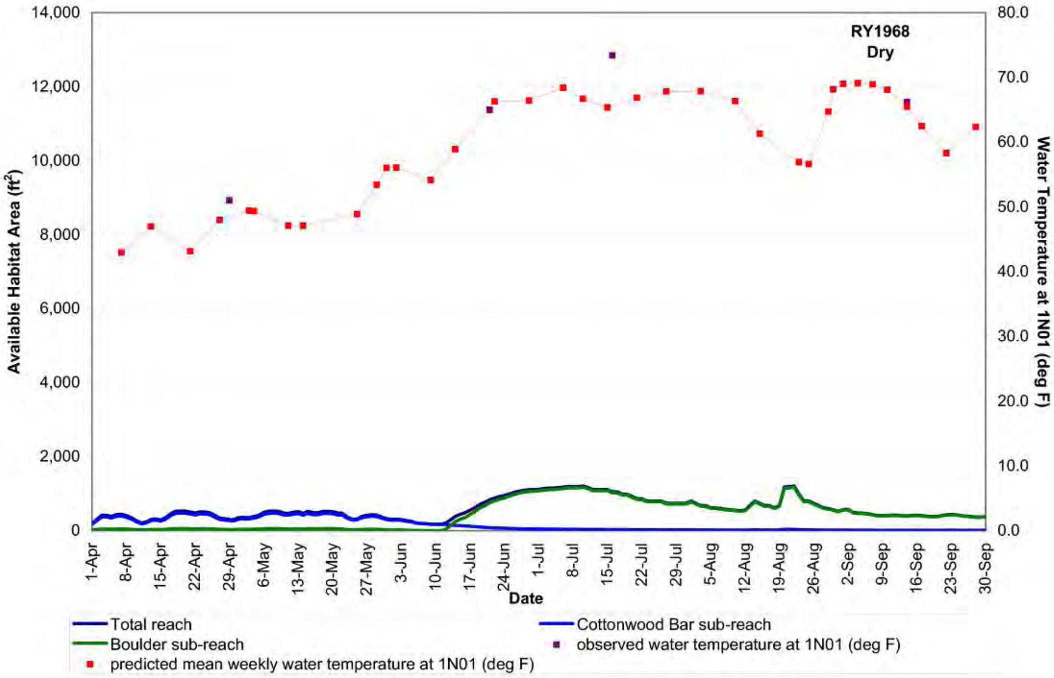


Figure 91. Habigraph for Pacific treefrog early-life stage on the Clavey River, RY1968 (Dry).

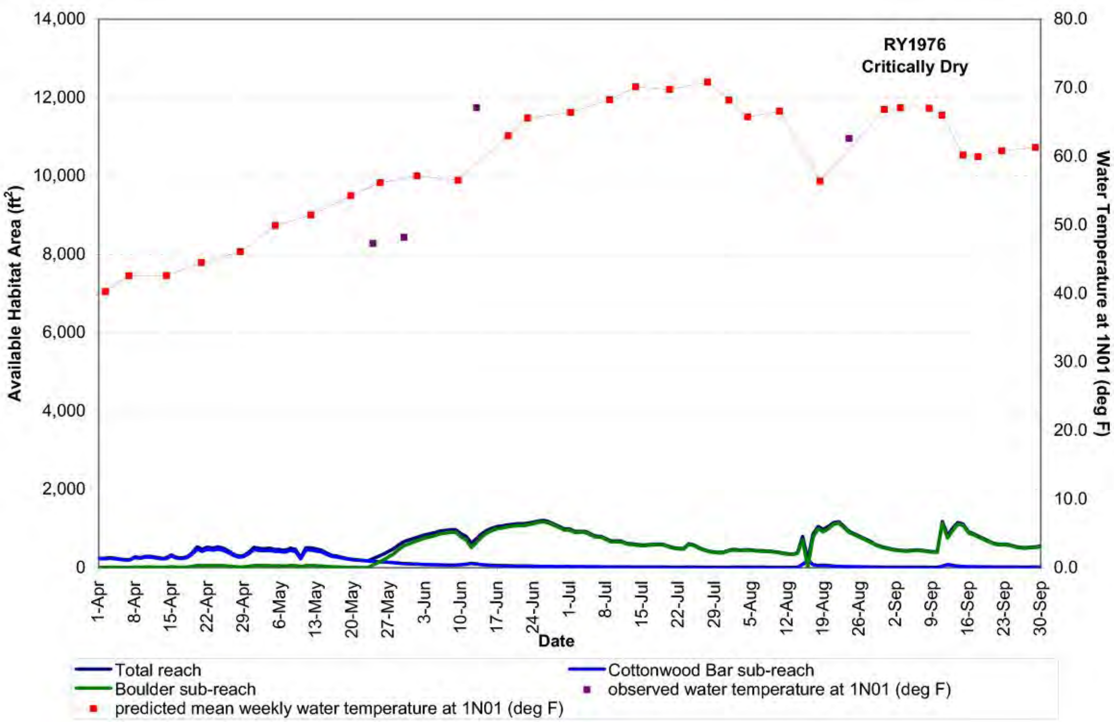


Figure 92. Habigraph for Pacific treefrog early-life stage on the Clavey River, RY1976 (Critically Dry).

Table 26. Estimated timing of Pacific treefrog life history stages on the Clavey River, by runoff year.

Runoff year	Runoff year type	Estimated life history timing						No. of days	
		Oviposition		Egg hatching		Metamorphosis		Ovipo-sition	Total breeding
		Begin	End[1]	Begin[2]	End[3]	Begin[4]	End[5]		
2005	Extremely Wet	Jun 16[6]	Jun 30	Jul 3	Jul 17	Aug 28	Sep 11	15	14
1973	Wet	Jun 3[7]	Jun 30	Jun 20	Jul 17	Aug 15	Sep 11	28	27
1971	Normal	Apr 18[8]	Jun 30	May 5	Jul 17	Jun 30	Sep 11	74	73
1968	Dry	Apr 1	Jun 30	Apr 18	Jul 17	Jun 13	Sep 11	91	90
1976	Critically Dry	Apr 1	Jun 30	Apr 18	Jul 17	Jun 13	Sep 11	91	90

[1] End of breeding window (Figure 45)
[2] 18 days after oviposition begins
[3] 18 days after oviposition ends
[4] 74 days after oviposition begins
[5] 74 days after oviposition ends
[6] Date when early-life Pacific treefrog habitat becomes available in Extremely Wet runoff year
[7] Date when early-life Pacific treefrog habitat becomes available in Wet runoff year
[8] Date when early-life Pacific treefrog habitat becomes available in Normal runoff year

3.4.8. Synthesizing Benthic Invertebrate Habitat, Daily Flows, the Snowmelt Hydrograph, Scour, and Desiccation

Benthic Macroinvertebrate Habitat Rating Curve

In the Clavey River study site, *complex* benthic macroinvertebrate habitat mapping was performed (complex refers to hydraulically complex; for detailed definition see the Benthic Macroinvertebrates subsection under Section 3.3.5) at five flows (12, 57, 184, 406, and 1112 cfs) (Figures 93 and 94). At the Clavey River study site, results from the depositional Cottonwood Bar sub-reach were isolated to compare complex macroinvertebrate habitat area with the boulder sub-reach (Figure 95). Mapping at several more flows would have smoothed this habitat rating curve, particularly between 300 cfs and 450 cfs. Most of Cottonwood Bar was not significantly inundated until 300 to 400 cfs. For the curve representing mapped habitat at the Cottonwood Bar sub-reach, an inflection point likely exists between 300 to 400 cfs. The curve representing the boulder sub-reach likely does not present an inflection point, because its curve generally slopes downward (Figure 95).

For Cherry Creek, the benthic macroinvertebrate habitat rating curve (Figure 96) displays the effect of woody riparian encroachment and deposition. At intermediate streamflows (approximately 200 cfs to 800 cfs), the depositional features that support open cobble bars are absent. Habitat is only available within the baseflow channel or at relatively high (and very infrequent) flows on Cherry Bar and on other larger depositional features with exposed patches among Ponderosa pines.

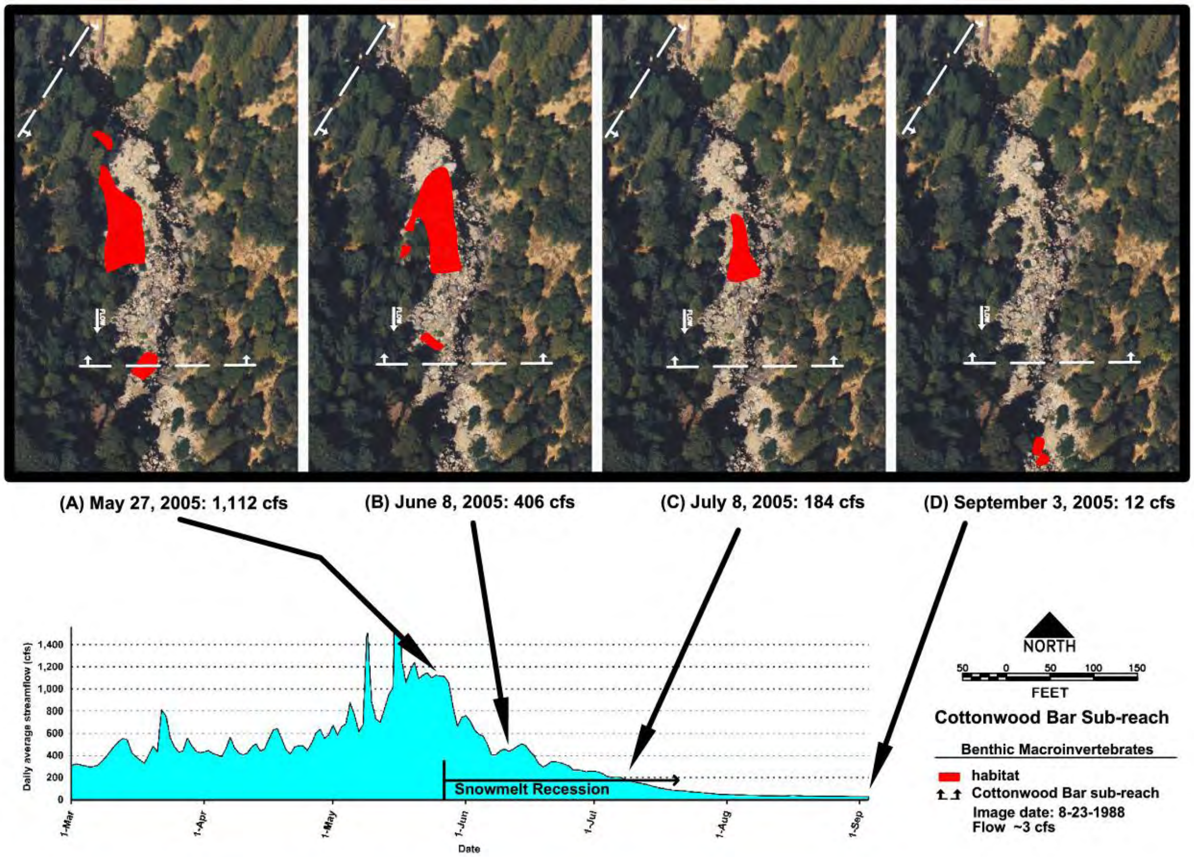


Figure 93. Benthic macroinvertebrate polygons from expert habitat mapping at 1112, 406, 184, and 12 cfs in the Clavey River study site, Cottonwood Bar sub-reach.

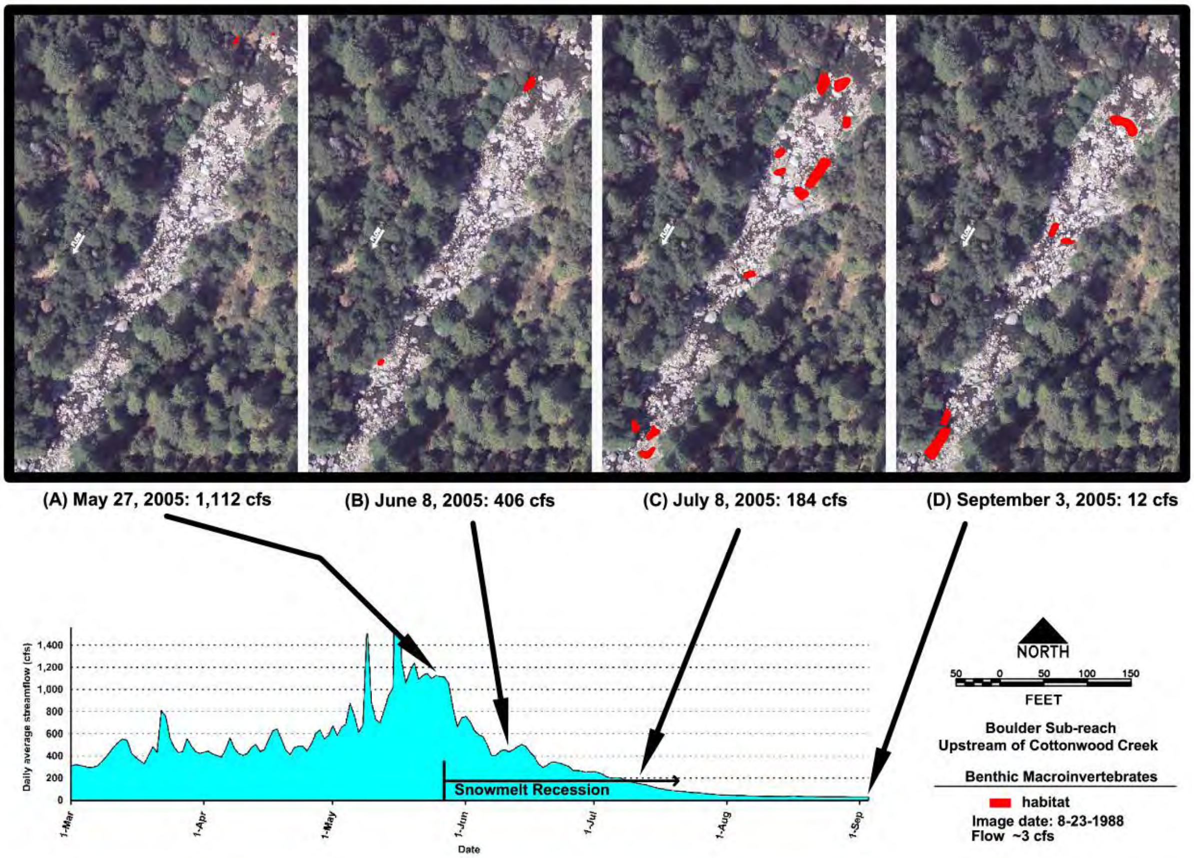


Figure 94. Benthic macroinvertebrate polygons from expert habitat mapping at 1112, 406, 184, and 12 cfs in the Clavey River study site, boulder sub-reach.

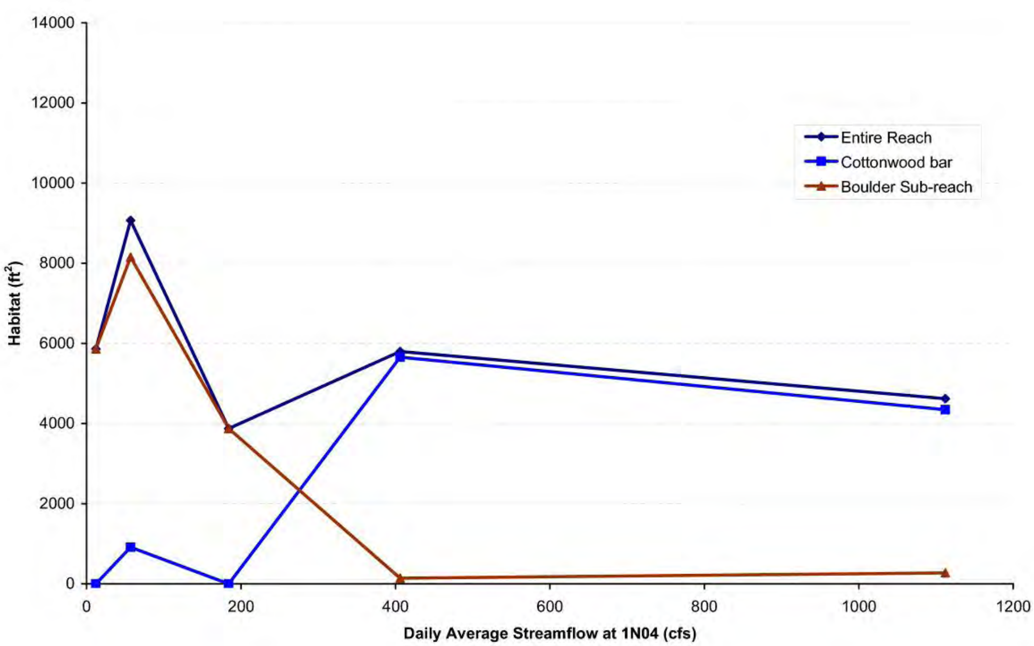


Figure 95. Benthic macroinvertebrate habitat rating curve for the Clavey River study site.

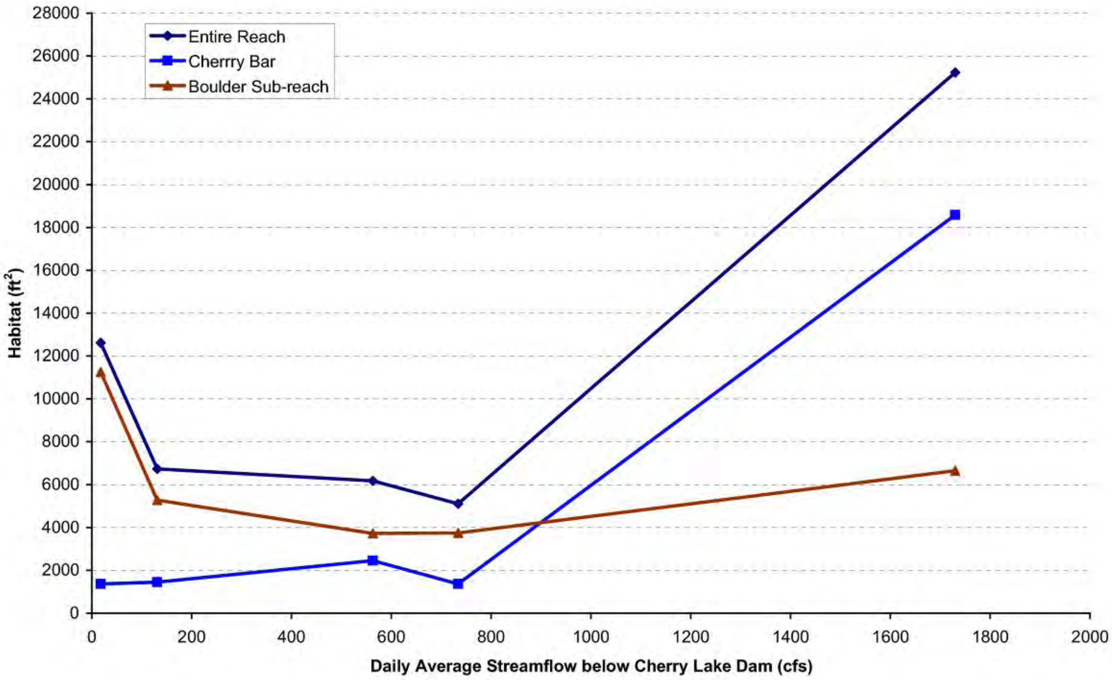


Figure 96. Benthic macroinvertebrate habitat rating curve for the Cherry Creek study site.

Benthic Macroinvertebrate Habigraphs

Water temperatures thresholds for each runoff year were superimposed onto habigraphs for benthic macroinvertebrates (Figures 97 to 101). Using the water temperature threshold range of 41°F to 55°F to define highly productive habitat (Benthic Macroinvertebrates, under Section 3.3.5), the amount of ecologically available habitat was quantified in the context of water temperatures, a productive temperature range, and a maximum temperature threshold (62°F), for each runoff year type. Two aspects of benthic macroinvertebrate habitat were quantified in ecologically available habitat area: (1) hydraulically complex riffle habitat regardless of water temperature, and (2) highly productive complex riffle habitat (i.e., complex habitat occurring during the snowmelt hydrograph when temperatures favor high productivity).

Benthic macroinvertebrate habitat trends are briefly summarized below:

RY2005 an Extremely Wet Runoff Year (Figure 97)

Highly productive and extensive macroinvertebrate habitat was sustained throughout the spring by inundating Cottonwood Bar. When streamflows decrease sharply in the recession period, water temperatures are just beginning to exceed the threshold for highly productive habitat.

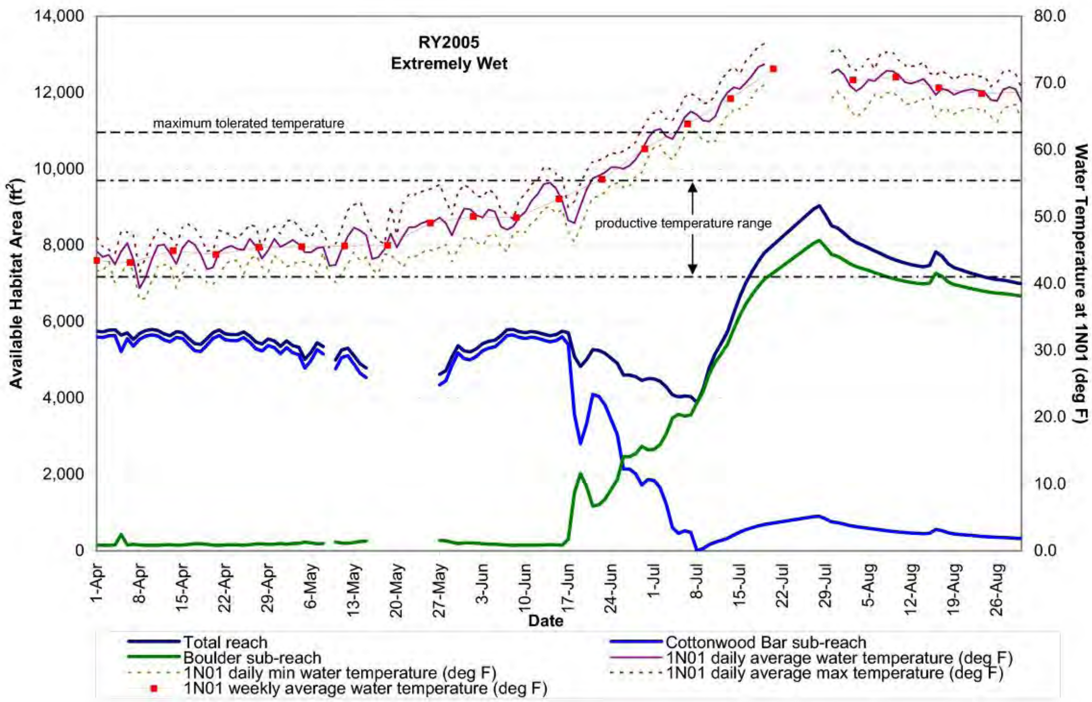


Figure 97. Habigraph for benthic macroinvertebrates on the Clavey River, RY2005 (Extremely Wet).

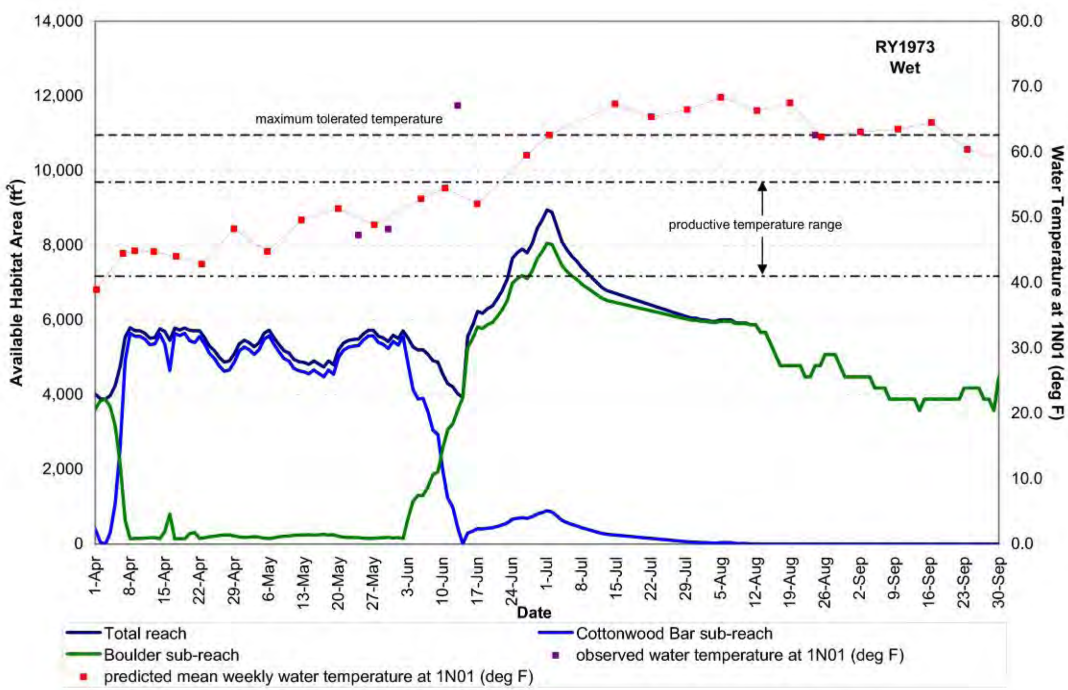


Figure 98. Habigraph for benthic macroinvertebrates on the Clavey River, RY1973 (Wet).

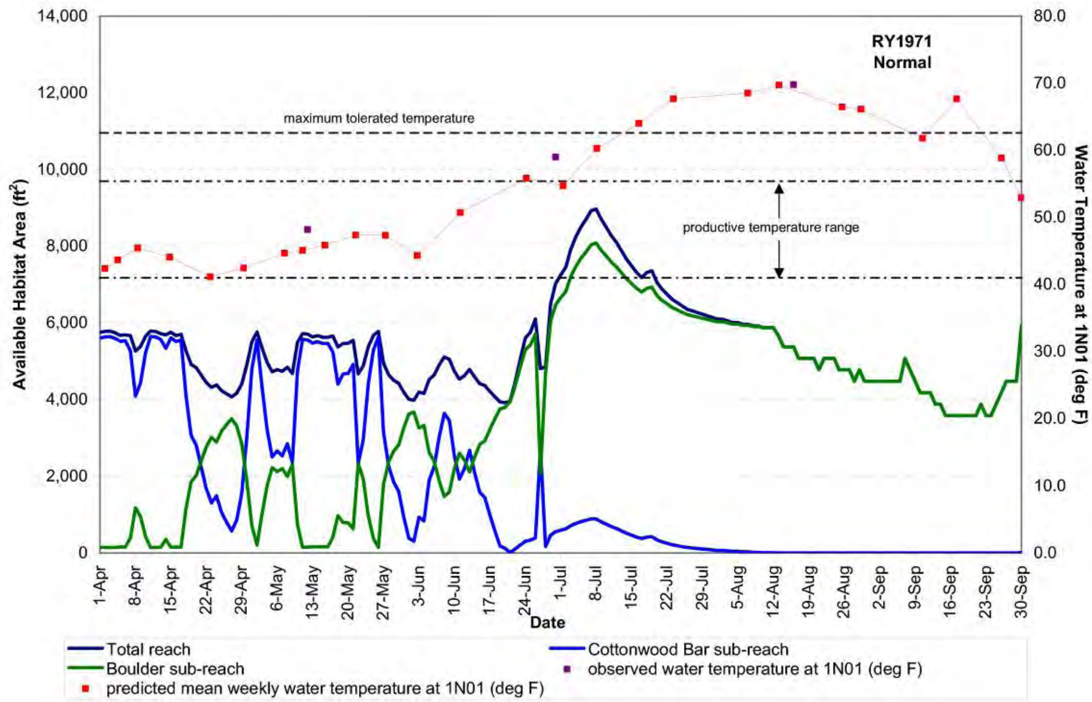


Figure 99. Habigraph for benthic macroinvertebrates on the Clavey River, RY1971 (Normal).

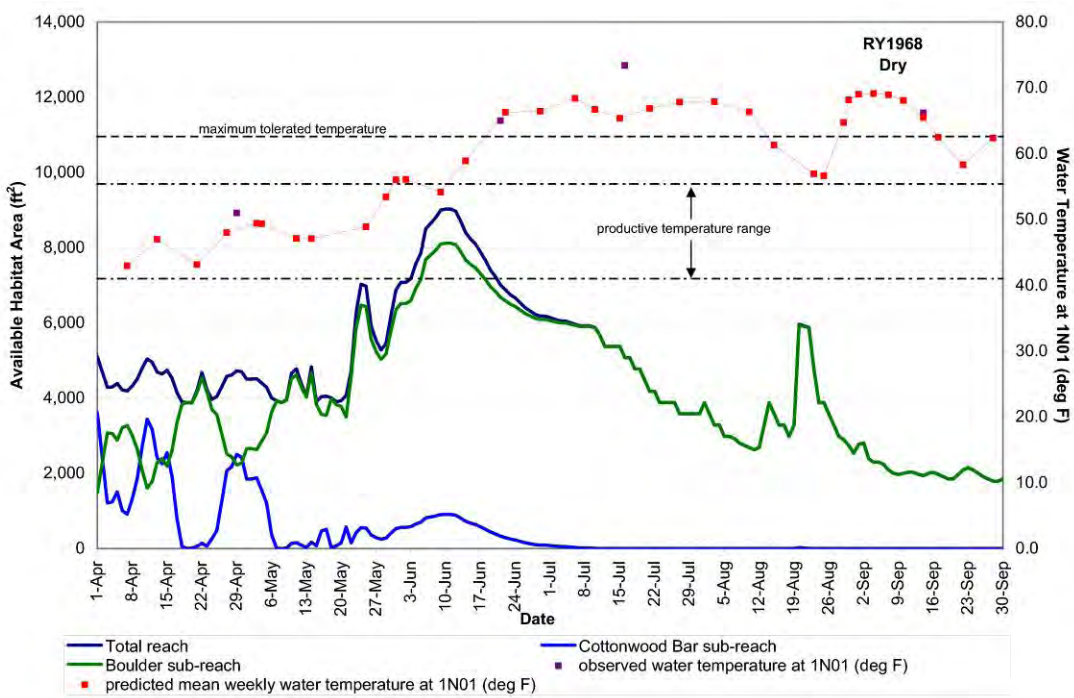


Figure 100. Habigraph for benthic macroinvertebrates on the Clavey River, RY1968 (Dry).

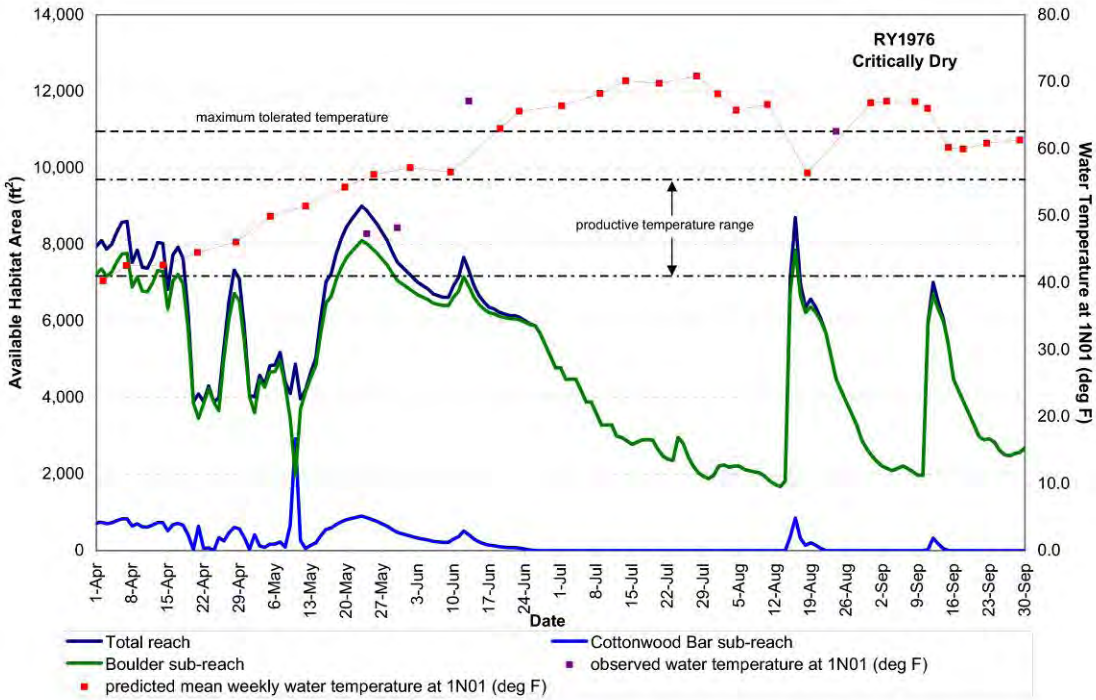


Figure 101. Habigraph for benthic macroinvertebrates on the Clavey River, RY1976 (Critically Dry).

In the Clavey River study reach at the snowmelt flow peak, the total amount of available habitat was roughly the same (approximately 9000 ft^2) across the different runoff years. When habitat area in the boulder sub-reach was low, habitat area in the large depositional sub-reach was high, and vice versa. Based solely on available habitat area, drier years provide as much habitat for benthic macroinvertebrates as wetter years.

However, when one considers productive and threshold temperatures, differences in ecologically available habitat between runoff year types become apparent. In wetter years, peak habitat area occurs later, when water temperatures exceed the "highly productive" temperature zone. In Extremely Wet RY2005, habitat area peaked when water temperature was greater than 70°F; in Critically Dry RY1976, habitat area peaked when water temperatures were in the mid-50s °F. So, while habitat availability is an important consideration, ecologically available habitat, when water temperature favors high benthic macroinvertebrate production, may be more important. The Wet and Extremely Wet runoff years sustained almost 6000 ft^2 of highly productive habitat through most of the spring just on Cottonwood Bar. Streamflows were too high to support complex habitat in the boulder sub-reach, but were sufficiently high to keep Cottonwood Bar inundated. When flows finally receded, water temperatures rose sharply past the optimal threshold. Complex habitat in the boulder sub-reach became available, but temperatures were now very high, thus providing poor habitat. A better defined habitat rating curve (i.e., providing at least two more data points at streamflows less than 400 cfs) would provide clearer habitat trends in relation to flows.

RY1973 a Wet Runoff Year (Figure 98)

Cottonwood Bar was inundated most of the spring, creating most of the complex habitat through May. Highly productive water temperatures coincided with this time period, lasing until mid-June. Most of the Wet runoff year's highly productive macroinvertebrate habitat originated from Cottonwood Bar. In the boulder sub-reach, by the time habitat becomes available in June, water temperatures are starting to exceed the productive temperature range. However, even at times other than when labeled highly productive, a patch of channelbed can still contribute to overall benthic macroinvertebrate productivity.

RY1971 a Normal Runoff Year (Figure 99)

Fluctuating flows during most of the snowmelt hydrograph, and without a distinct peak, intermittently inundated Cottonwood Bar. Total habitat area appears relatively steady into July, but it is the sum of numerous habitat tradeoffs between the Cottonwood Bar and boulder sub-reaches. Similar to the pattern of the Wet runoff year, once ecologically available habitat area of the boulder sub-reach begins to increase, water temperatures begin to exceed the productive temperature range.

RY1968 a Dry Runoff Year (Figure 100)

Cottonwood Bar was infrequently and just barely inundated during peak snowmelt runoff from late-March through early-May. Consequently, during that time, most complex macroinvertebrate habitat was derived from inundating small depositional features within the boulder sub-reach, not from inundating large depositional features. Rising snowmelt flows did occur when water temperatures were within the highly productive temperature range, thus creating a sharp increase in highly productive macroinvertebrate habitat attributed almost entirely to the boulder sub-reach. Note that the period of highly productive habitat extended through May. Though ecologically available habitat remained high during peak runoff and the early portion of the recession limb, water temperatures were already climbing outside the highly productive temperature range by early June.

RY1976 a Critically Dry Runoff Year (Figure 101)

In a Critically Dry runoff year, high snowmelt flows are essentially missing. With flows limited to the active channel, almost all complex habitat and highly productive benthic macroinvertebrate habitat occurs in the boulder sub-reach. Highly productive habitat lasts until approximately May 20.

3.5. Water Temperature in Space and Time

As displayed by the species' habigraphs, water temperature is a key environmental cue affecting the timing of many life stages. Water temperatures appearing on the habigraphs are derived from the SNTEMP model, from the gaging station at the 1N01 Bridge that is 7.6 river miles downstream from the Clavey River study site, and from spot checks during field surveys (Section 2.3.1). Water temperatures derived from these methods are subject to uncertainty, but water temperatures will vary spatially and temporally based on physical processes. The physical processes affecting water temperature include insolation, mixing, and thermal stratification.

The heating effects of insolation and mixing will depend on the water year type; water temperatures in Dry years are likely to be warmer and will likely extend farther upstream than those in Wet years. Thus, a flow isotherm will vary spatially by moving up- and downstream (a phenomenon referred to here as the *trombone effect*). Water temperatures exceeding 70°F (approximately 21°C) have been modeled along the mainstem Clavey River (EA Engineering 1987). The upstream extents of temperatures greater than 70°F were modeled during three water year types: WY1977 (Dry), WY1979 (Normal), and WY1982 and WY1986 (Wet). A 70°F threshold was selected because this heat will begin to stress cold water species, such as rainbow trout. As expected, the 70°F threshold line moves up and downstream depending on water year type, and loosely represents (or tracks) the line that divides the dominance of cold and warm water aquatic species.

Even if downstream of the 70°F threshold line, aquatic organisms can still survive by finding temporary thermal refuge deep in stratified pools. Stratification occurs when flows decrease, and the average residence time of water in the pool increases. Residence time equals pool volume (cubic feet, ft^3) divided by streamflow (cfs). A residence time greater than 0.25 hr to 0.50 hr can degrade water quality, water temperature, and benthic invertebrate drift (Ott Water Engineers 1985). Differences of 3°C and greater have been recorded between surface and bottom water temperatures in deep pools in Northern California streams (Nielsen et al. 1994). In that study, residence times of 2.5 to 9.3 hours were identified for stratified pools; the authors also note that the unstratified pools examined in the Eel River had residence times less than one hour.

Deep pools are a trademark of the mainstem Clavey River, especially downstream of the 1N01 Bridge, and residence times can be estimated for pools visible in aerial photographs. The Clavey River's lower mainstem was not included in this one-year project, but referring to aerial photography and field notes, for an average large and deep pool, the dimensions are commonly 150 ft by 25 ft by 6 ft (l x w x d), for a total volume of 22,500 ft^3. There are many larger pools. A residence time of 1 hr for this common pool size, requires a flow of 6.25 cfs; a pool 150 ft by 30 ft by 8 ft (l x w x d) is still common, and would require 10 cfs. Decreasing flows from July and into August that approach 10 cfs to 15 cfs typically occur very late in the snowmelt recession period or afterwards, depending on how the end of the snowmelt recession period has been determined.

Thermal stratification of pools can provide refuge as stressful water temperatures are encountered upstream into late-summer. Baseflows that are augmented by reservoir releases to improve trout habitat (by decreasing surface water temperatures), can prevent or delay stratification of deep pools; reservoir releases could cause pools to mix.

3.6. Synthesis Implications

The Clavey River provided data that allowed exploration of a methodology for formulating pulse flow guidelines. The Clavey River was selected as one example of an unregulated boulder-bedrock Sierra Nevada river ecosystem. The project's results should be interpreted as indications that this methodology can be useful, but the project's specific results should not be applied as pulse flow guidelines for other river/reservoir systems.

3.6.1. Geomorphic Roles of Natural Snowmelt Streamflows

Channel morphology exerts a huge influence on ecological function and requires constant maintenance and renewal, especially for depositional features associated with nested hydraulic controls. Large depositional features (such as Cottonwood Bar) compared to small depositional features (such as gravel tail deposits between boulders) likely require different hydrologic events for maintenance and renewal. No single size, type, or frequency of flood event fulfills all these requirements.

In this study, the annual snowmelt peak and recession flows had a smaller role in geomorphic processes than initially anticipated. Flood magnitudes of annual snowmelt runoff peaks were generally too small to exceed most flow thresholds for mobilizing depositional features that often function as hydraulic controls. On the Clavey River, snowmelt-driven floods (typically achieving < 5-yr annual maximum peak floods) had minor influences that almost always occurred on depositional features in the study reach. Many gravel tail deposits at the channel thalweg were loosely consolidated and appeared to have been significantly mobilized. The 4.4-yr annual maximum flood of WY2005 partially reshaped some lee deposits of sand and gravel associated with boulder ribs.

With most snowmelt peak flood magnitudes being less than 5-yr floods, distinguishing the effects of a 2-yr flood magnitude from a 4-yr flood magnitude, for example, could be important for formulating snowmelt pulse flows. Without such a distinction, one cannot anticipate if the release of 1.5-yr floods would achieve the same geomorphic results as the release of 4.0-yr floods. Within the project's timeframe, there was no simple way to quantify this differentiation. Hydraulic modeling of bed scour was disappointing due to the large depositional features and smaller features associated with complex secondary hydraulic controls. Run and pool tail deposits often provide rainbow trout spawning habitat and are in relatively simpler hydraulic environments; hydraulic modeling was expected to perform better. However, the results were barely believable. Flows as low as 400 cfs could theoretically mobilize the surfaces of gravel tail deposits close to the thalweg, but significant mobilization likely occurs above 800 cfs to 1000 cfs. A clear geomorphic role of flood peaks between 1.5-yr and 5.0-yr annual maximum flood recurrences is to mobilize the surfaces of most tail deposits and to significantly scour (more than two D_{84} surface particle diameters deep) most of those tail deposits close to the channel thalweg.

Another process having minor geomorphic significance but important biological significance is the scour of the fine-grained matrix between coarse particles that comprise depositional features. Seedlings that germinate in this fine matrix are extremely vulnerable. Snowmelt floods and small winter floods (< 5-yr), and even the smallest of annual maximum floods (1.5-yr or smaller), may generate local scour of the matrix sufficient to fatally damage or remove seedlings in selected depositional features. Changing the magnitude, frequency, and timing of these "minor" flood peaks could widen the windows of opportunity for seedling survival (i.e., early establishment), as they grow through their first winter floods and second snowmelt peak and recession flows. Although four mobilization actions that 1.5- to 3-yr floods can accomplish (Section 3.2.5) are defined, the flow threshold for scouring of fine-grained matrix in each type of depositional feature remains undefined.

3.6.2. Biological Roles of Natural Snowmelt Streamflows

While geomorphic evaluation of the snowmelt hydrograph focused on the magnitude of the snowmelt peak, the biological evaluation considered all snowmelt hydrograph components: the snowmelt rising limb, snowmelt peak, and both fast and slow snowmelt recession limbs. Each snowmelt hydrograph component has its characteristic magnitude, duration, frequency, and timing; these characteristics profoundly influence habitat quality and abundance for native riparian plants and aquatic animals.

One of the primary biological implications of synthesizing the river's geomorphology, snowmelt hydrology, water temperature, and species life history is that variation in water year types is required if a river is to support a variety of species. This concept is not new (Poff and Ward 1989; Wootton et al. 1996; Lytle and Poff 2004). During different water year types, the variation in snowmelt flow magnitude, frequency, duration, and timing will create good habitat conditions in some years for some species, and bad conditions in other years for other species. These "good with the bad" conditions are natural; therefore, the ecological goal of pulse flow releases should be to allow good and bad to happen naturally.

This goal of desired and required variations in pulse flow releases is not the apparent goal in most reservoir release programs. For example, higher than natural summer baseflow releases are often prescribed, because more pool habitat for trout will be produced, presumably leading to larger trout. Many regulated Sierra Nevada rivers and elsewhere are managed so that releases benefit a single species; for example, in traditional PHABSIM analyses, fish biologists strive for a release that creates the optimal flow, which produces the most trout habitat. However, releases favoring trout habitat may create water temperature conditions that are unsuitable for other native species, such as amphibians, benthic macroinvertebrates, or turtles.

Therefore, a better ecological goal for pulse flow releases is to allow "good and bad" conditions to happen naturally.

The life history of woody riparian vegetation, considered with the snowmelt hydrograph's components and the river's depositional/scour features, exemplifies the "good with bad" conditions requirement. Depositional features can be ideal micro-environments for seedling germination and establishment, yet in the RY2005 Clavey River mainstem channel, many of these features were either sparsely colonized with very young plants or not at all. Clearly, the woody riparian vegetation in the Clavey River is not experiencing good conditions every year.

For woody riparian vegetation, especially the willows, seed release begins in May, coinciding with snowmelt; there is an almost continuous rain or rafting of viable seeds onto depositional features. Arroyo willow releases seeds in May, followed by Jepson's and shiny willow in June, then dusky willow in July and August. Meanwhile white alder seeds, remaining viable longer than a year, are rafted onto bars and deposits by winter floods or snowmelt peak flows. Therefore, for willow species and white alders, seed release periods occupy unique but overlapping positions along the snowmelt hydrograph.

The Clavey River's unregulated annual snowmelt flows discourage germination and seedling success by desiccation, inundation, and scour. In drier runoff years, many depositional features, particularly large ones as Cottonwood Bar, are never inundated, making them inhospitable to seed germination. In most runoff years, during the snowmelt recession flows, the water surface elevations decrease so rapidly that young seedlings are killed because their roots cannot grow fast enough. Sudden flow increases during the recession periods may kill or weaken the seedlings by inundating and/or scouring the fine matrix in which seedlings are delicately rooted. During Normal, Wet, and Extremely Wet runoff years, by releasing its seeds later than other willow species, dusky willow has the best opportunity for establishing seedlings along the margins of big bars or on small depositional features within the baseflow channel. During the period represented by the slow recession limb of the snowmelt hydrograph, changes in stage happen more slowly, and root growth need not be as fast.

The observation of few seedlings in late summer, and the modeling results of initiation/early establishment, indicated that the Clavey River mainstem is a hostile environment for willows. Very few seedlings survive the summer, other than dusky willow seedlings that initiate close to the summer baseflow channel, because the fast snowmelt recession flows strands them. Smaller depositional features, such as lee deposits, may stay inundated during the willows' entire seed release periods. Again, by releasing seeds late, dusky willow can germinate on these moist features, once exposed by receding snowmelt flows.

Winter floods, and to a much lesser extent snowmelt peaks, are formidable conditions that a seedling must survive to live to its second summer. Drier years that favor initiation are also the years that carry the most risk of winter and snowmelt scour because initiation is located within the baseflow channel where scour is most likely. The combination of winter floods and flows represented by the snowmelt hydrograph is instrumental in maintaining sparsely vegetated depositional features in the mainstem Clavey River.

For rainbow trout, California roach, foothill yellow-legged frogs, western toad, Pacific treefrog, and benthic macroinvertebrates in the Clavey River, ecologically available habitat area depends on the annual snowmelt hydrograph. Each of these species' life history findings depended on the magnitude, duration, timing, and rate of all components of each runoff year's snowmelt hydrograph. For example, in Wet runoff years, benthic macroinvertebrate habitat is ecologically available, but in Dry runoff years productive habitat is highly limited.

No one runoff year remotely approached providing ideal, or even good, habitat conditions for all species examined. As constructed for selected species life stages using expert habitat mapping, habitat rating curves and habigraphs document that large depositional features provide ecologically available habitat during higher snowmelt, while the baseflow channel provided ecologically available habitat during low snowmelt flows.

Stream temperature in the mainstem Clavey River varies spatially and temporally. Flows represented by both snowmelt recession limbs, but especially the slow limb, occur when air temperatures rise sharply. In Dry water years, stream temperatures from June through early September are likely to be warmer, to warm earlier, and to extend farther upstream than in Wet water years. The interannual migration of a 70°F temperature isotherm up and down the mainstem (the *trombone effect*), depending on the runoff year, loosely follows the dominance between cold and warm water aquatic species. Therefore the magnitude, duration, rate, and timing of the slow recession flows dominate this annual thermal outcome. Cold water species trapped downstream in 70° F water can take advantage of thermally stratified pools. Deep bedrock pools won't stratify when streamflows are higher than unregulated low summer baseflows. In regulated rivers, releasing higher than natural summer baseflows intended to create additional rainbow trout pool habitat could destratify (mix) these thermal refugia.

3.6.3. Geomorphic Roles of Natural Winter Floods

Winter floods perform most geomorphic work in the boulder-bedrock Clavey River mainstem. The winter flood hydrograph exhibits extremely steep rising and falling limbs, with a brief but often considerable peak magnitude. Although these floods typically occur in winter, late-fall or early-spring floods are not rare. In Wet water years, several winter peak floods often occur in close sequence. Not only does the natural winter flood provide almost all the biggest floods (> 40-yr flood peak), it also provides large floods (between 15-yr and 40-yr flood peaks), and most intermediate floods (between 5-yr and 15-yr flood peaks). Before the project, snowmelt flows were considered to be important geomorphic agents for change; the project results instructed us otherwise. However, the relative geomorphic importance of winter floods versus snowmelt floods changes depending on location within the basin. Mainstem channel segments that are situated higher in the Clavey River watershed will experience almost exclusively snowmelt-generated floods. Farther downstream, rainfall generated floods and rain-on-snow floods are more likely. The project study site was located well within this snow-to-rain transition zone, as are many regulated mainstem segments of other Sierra Nevada rivers.

The interannual variation of winter peak floods is what maintains a dynamic balance of nested hydraulic controls; this balance ultimately controls small- and large-scale depositional features. Effects of a 5-yr flood peak and 75-yr flood peak were observed, and effects of 12-yr to 15-yr flood peaks were estimated. The WY1997 flood, a 75-yr annual maximum flood event, accomplished several surprising tasks even though it was not sufficiently big to mobilize many primary hydraulic controls. Boulder ribs were differentially affected. In a few locations, minor boulder ribs were removed or initiated, while the dominant boulders in large boulder ribs remained intact. Cottonwood Bar aggraded with large cobbles and occasional small boulders. Many lee and obstruction deposits of large cobbles and/or small boulders were significantly reshaped. In contrast, the WY2005 5-yr annual maximum flood accomplished surprisingly little. Gravel deposits in run and pool tails were mobilized, though not extensively. Most lee and obstruction deposits and small bar features were unaffected by the WY2005 5-yr flood, possibly because the boulder ribs functioned as effective secondary hydraulic controls. WY1982's 12-yr flood peak appeared to have significantly mobilized lee and obstruction deposits, to the extent that prior woody riparian vegetation was removed or sheared away. While a 5-yr flood barely overtops most boulder ribs, a 12-yr to 15-yr flood peak does so easily, even though the boulder rib still remains an effective secondary hydraulic control. This could make lee deposits more prone to scour than obstruction deposits, i.e., plunging flood flows cascade over the boulder rib and scour the downstream lee deposit without similarly scouring the obstruction bar upstream of the boulder rib. A 40-yr flood peak may be necessary to provide flows high enough to prevent most boulder ribs from acting as secondary hydraulic controls.

3.6.4. Biological Roles of Natural Winter Floods

While the mechanisms of desiccation and seedling scour during the snowmelt recession flows are highly effective in suppressing establishment, neither is 100% effective, so a few seedlings survive to experience winter floods. As important as winter flood magnitude is, winter flood frequency may be equally important; for example, a 2-yr old seedling is much easier to scour than a 4-yr old seedling. Therefore, pulse flows that mimic the magnitude and frequency of larger natural winter flood peaks will be extremely important in maintaining river ecosystems.

Woody riparian vegetation can become established within the actively scoured mainstem channel and then survive 5-yr to 10-yr flood peaks. However, the bigger and less-frequent floods, typically winter floods, but occasionally snowmelt rain-on-snow floods, act as reset buttons. Entire willow or alder stands can be scoured from larger depositional features, and single trees in the lee of boulder ribs are either entirely scoured or sheared off. The sequence of water years following the WY1986 flood, and leading up to the WY1997 flood, was relatively benign and encouraged widespread plant colonization. The 75-yr WY1997 flood peak transformed Cottonwood Bar from a relatively lush environment to one mostly barren of woody riparian vegetation on the surface. But it was not a resetting "mega-flood" because many willows survived below ground. By WY2005, willows had already conspicuously begun to recover, mostly from the regrowth of sheared-off stems that survived the WY1997 flood, rather than from the germination of new plants.

Winter floods also can affect the age class structure of mature woody riparian species. During winter-sized floods (e.g., greater than 10-yr recurrences), the active channel is extremely dynamic. High velocities, cobbles and small boulders bouncing over boulder ribs, hydraulic jumps passing through bedrock pools, and occasional floating debris, can shear and/or severely damage exposed trees. To bend is highly adaptive, but as trees grow, they become more rigid. Trees 9 years to 10 years old and older are much more rigid than younger trees. In the mainstem Clavey River, 10-yr old white alder, shiny willow, or red willow in ideal growing conditions can be 20 ft tall with a 0.5 ft diameter stem. Riparian trees older than 10 years in the boulder-bedrock reaches were invariably located in the lee of large, protecting boulders. Dusky willows, more bush than tree, easily rebounded from having branches sheared in WY1997.

The January 1997 flood did mobilize many portions of the channelbed and depositional features, but sometimes mobilization occurred in unanticipated ways. Rather then scour Cottonwood Bar, this flood aggraded the bar's surface with small boulders. Many depressions that dotted Cottonwood Bar's surface in the 1993 aerial photographs and that held standing water into late August were missing in 2000. Amphibians, such as foothill yellow-legged frogs, lost their high-quality habitat. Future 15-yr to 20-yr flood peaks, which will likely scour those trees thriving in the scour holes located below the boulder ribs and depressions around prominent boulders, may return Cottonwood Bar's surface to its 1993 condition.

Many biological hotspots are simply short channel segments where the effects of the winter flood(s) and the snowmelt flows are slightly less severe. For white alders and bigleaf maples, the inside of a wide, sharp channel bend can secure just enough protection from flood effects (i.e., by creating a large eddy effect), so that relatively old rigid trees survive. But without both hydrograph components, the ecological richness of these hotspots would likely disappear.

Cottonwood Bar is a biological hotspot in the middle mainstem Clavey River. Located on a broad channel bend just upstream of a primary hydraulic bedrock control, Cottonwood Bar is a major depositional feature that has one of the river's few aggraded floodplains, an active side channel, and a mosaic of finer depositional features across its bar surface. These diverse physical habitats sustain a diversity of plants and animals. Here, the snowmelt flows increase the bar's habitat potential. If spring releases are limited to baseflows (as occurs if releases are based on a habitat-flow relationship for rainbow trout adult rearing or spawning) flow would remain in the active baseflow channel, and this reach of mainstem channel would become almost indistinguishable from the other reaches.

3.6.5. Reference Conditions

The snowmelt hydrograph may be more of a biological, than geomorphic, force shaping Sierra Nevada river ecosystems. As constructed from expert habitat mapping, the habitat rating curves and annual habigraphs demonstrate how the annual snowmelt hydrograph and thermograph dominate favorable habitat conditions. So, the flow management question becomes: how much flow can be diverted from natural pulse flows (winter floods and annual snowmelt hydrographs), while maintaining river ecosystem integrity? To answer this question, the concept of a reference condition was employed (see Section 2.5). To prescribe pulse flows, the ecological goal is to recommend a daily diversion rate during the snowmelt hydrograph that causes as little divergence from the reference condition curves (one for each species and life stage) as possible.

One of the primary biological implications of this synthesis is that variation in water year types is required if a river is to support a variety of species. Reference conditions were computed for the five sample runoff years to account for natural interannual variability. This implies that no single reference condition can adequately support the many species and life stages. The critical job for the scientist/river manager is to select the most important (and hopefully, quantifiable) life history requirements and physical processes, while recognizing that other life history requirements will likely be affected. The more elegant and simple the selections, the more likely each will be understood and supported by all concerned parties.

Reference condition curves were graphed for the entire Clavey River study site, for the following species and life stages, among the five selected runoff years: RY2005 (Extremely Wet), RY1973 (Wet), RY1971 (Normal), RY1968 (Dry) and RY1976 (Critically Dry):

- Pacific Tree Frog Oviposition Habitat
- Pacific Tree Frog Egg Hatching to Metamorphosis Habitat
- Western Toad Oviposition Habitat
- Western Toad Egg Hatching to Metamorphosis Habitat
- Foothill Yellow-Legged Frog Oviposition Habitat
- Foothill Yellow-Legged Frog Oviposition Habitat
- Highly Productive Benthic Macroinvertebrate Habitat
- California Roach Fry Habitat
- Rainbow Trout Spawning Habitat
- Rainbow Trout Fry Rearing Habitat
- Rainbow Trout Adult Pool Habitat

Ranging up to a fixed daily diversion rate of 90% of the snowmelt hydrograph for all these habitats, reference condition curves were plotted together for each runoff year (Figures 102 to 106).

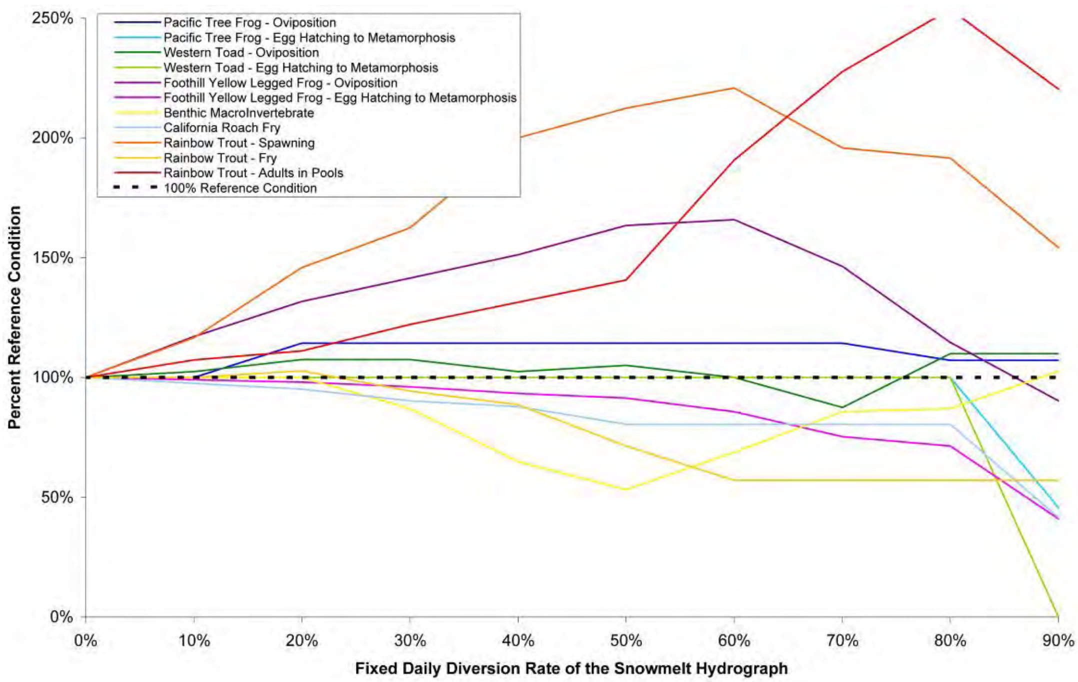


Figure 102. Reference condition curves for selected species and life stages when percentages of the snowmelt hydrograph are impounded on the Clavey River, RY2005 (Extremely Wet).

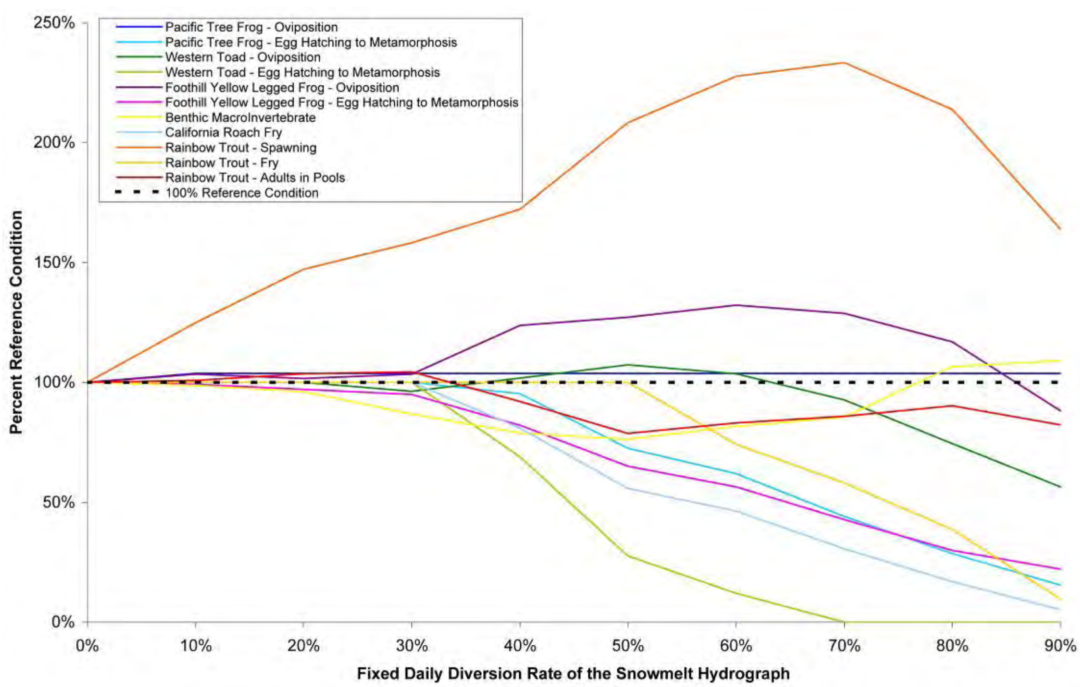


Figure 103. Reference condition curves for selected species and life stages when percentages of the snowmelt hydrograph are impounded on the Clavey River, RY1973 (Wet).

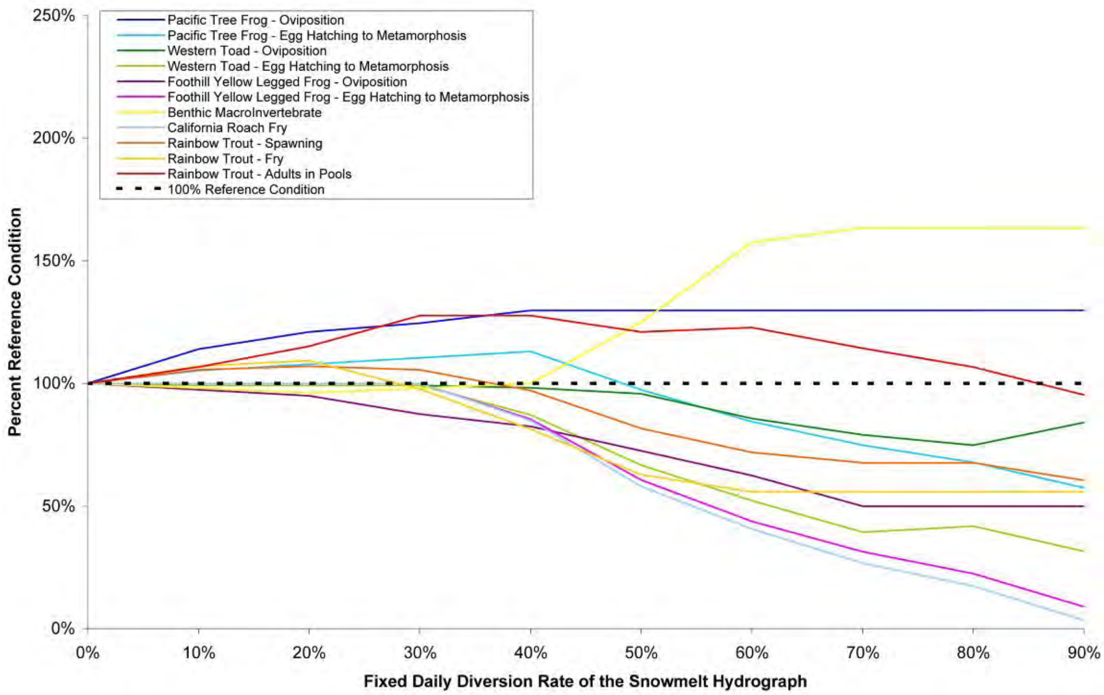


Figure 104. Reference condition curves for selected species and life stages when percentages of the snowmelt hydrograph are impounded on the Clavey River, RY1971 (Normal).

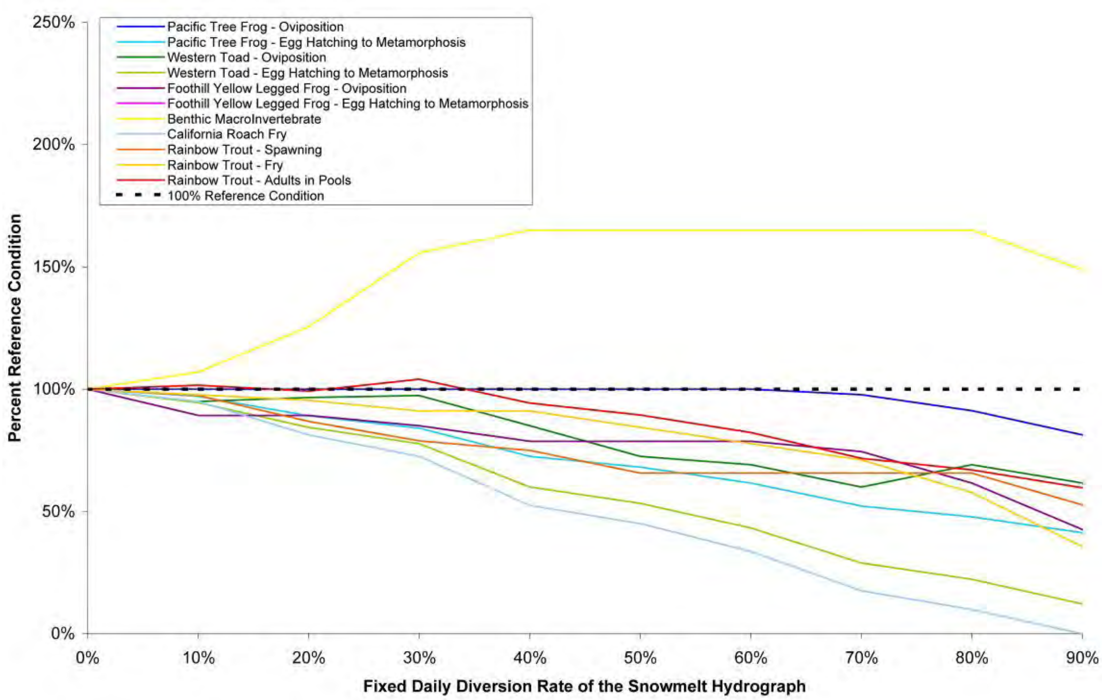


Figure 105. Reference condition curves for selected species and life stages when percentages of the snowmelt hydrograph are impounded on the Clavey River, RY1968 (Dry).

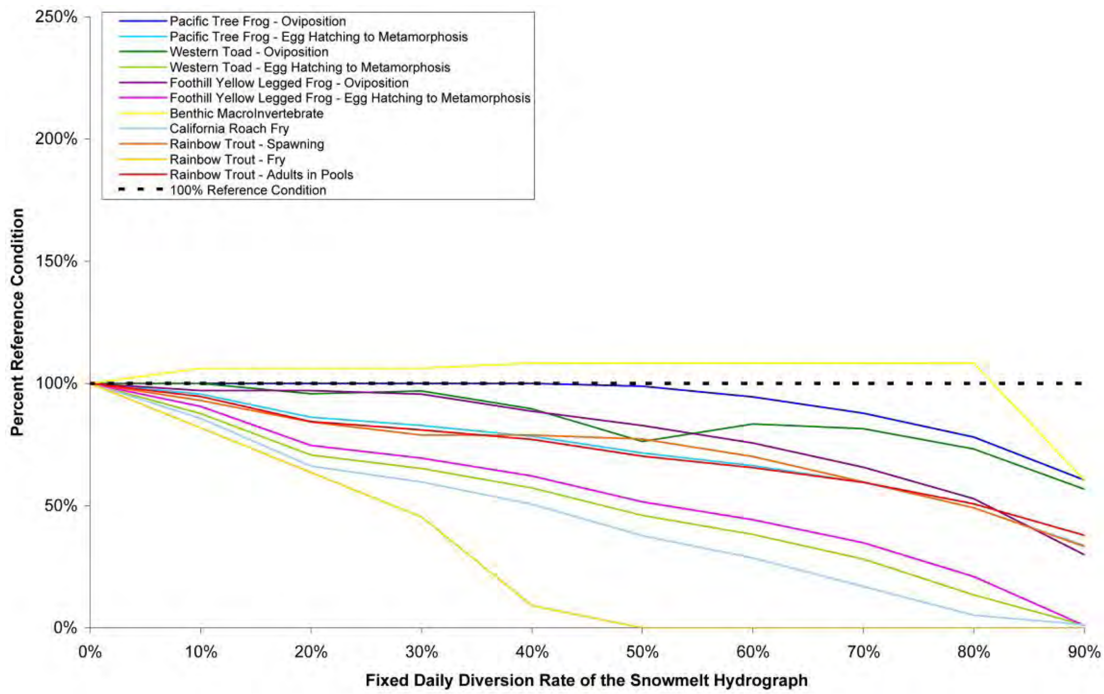


Figure 106. Reference condition curves for selected species and life stages when percentages of the snowmelt hydrograph are impounded on the Clavey River, RY1976 (Critically Dry).

Again, the ecological goal for prescribing pulse flows is to diverge from the reference condition as little as possible. So, an acceptable flow diversion rate during the snowmelt hydrograph period should remain close to the 100% line. If an acceptable change in reference condition is +/- approximately 25%, then inspection of Figures 102 to 106 indicates that an acceptable daily diversion rate ranges from 25% to 30%. The runoff year with the clearest acceptable diversion rate is RY1973 (Wet) (Figure 103), with the exception of the reference curve for rainbow trout spawning. During RY1973, the reference condition curves remain close to 100% until a diversion rate of 30% is reached. The pattern of the rainbow trout spawning reference condition curve reflects that life stage's narrow temporal window of ecologically available habitat (a small increase in available days generates a large percentage increase in reference condition). Possible acceptable daily diversion rates, as estimated from runoff years' reference curves are as follows:

- For RY2005 (Extremely Wet), 20% acknowledging the favoring of rainbow trout life stages and foothill yellow-legged frog oviposition habitat.
- For RY1973 (Wet), 30% with the exception of favoring rainbow trout spawning habitat.
- For RY1971 (Normal), 40%.
- For RY1968 (Dry), 30%.
- For RY1976 (Critically Dry), 20%.

This reference condition analytical approach differs fundamentally from the classical PHABSIM approach. While using the same basic habitat rating and availability curves, no “optimal” streamflow concept (the streamflow with the greatest habitat abundance) drives the analysis. Instead, a range of streamflows supplying abundant habitat is established by the project biologists (and/or by a sub-group of peer biologists) from the habitat rating curves. This range includes the streamflow supplying the most mapped habitat, but also higher and lower streamflows supplying more than 60% to 80% of the most habitat mapped at a single streamflow. Focusing on a range of flows that provide abundant (but not necessarily the most) habitat provides more operational reservoir management options. Further, the risk analyses for rainbow trout spawning and foothill yellow-legged frog early life stages indicate that habitat location and the timing and magnitude of snowmelt flows can be equally, if not more, important than habitat abundance.

3.7. Example Pulse Flow Guidelines

Due to the pilot study nature of the project, the focus was on determining whether this methodology could ultimately be used to formulate pulse flow guidelines. Many sources of uncertainty have been identified and described in previous sections, and readers are cautioned that these results have general application but should not be specifically applied to other Sierra boulder-bedrock rivers without similar and more detailed study. These examples of pulse flow guidelines indicate that this methodology can formulate said guidelines, and they demonstrate the level of quantitative detail possible.

The following three example pulse flow guidelines emphasize that pulse flows are not simply driven by flow magnitude (Table 27). Duration, frequency, timing, and variation of pulse flows are critical to protecting and/or restoring river ecosystem integrity. Together, these three example pulse flow guidelines should provide a useful starting point from which to evaluate existing and future operations.

Most dam operators in the Sierra Nevada would have difficulty implementing all three example pulse flow strategies, especially the first guideline. Many dam operations were not designed to release snowmelt flows or winter floods, but instead were designed to completely capture them for later gradual release through turbines during summer and early fall. Spillways for releasing big flows generally require full reservoirs before spilling. Therefore, unless spillways are redesigned, releasing most unregulated winter flood peaks will primarily depend on a reservoir’s capacity relative to total annual runoff and the timing of runoff in any particular water year.

Table 27. Example pulse flow guidelines for a boulder-bedrock stream in the Sierra Nevada. Guidelines are generally applicable, but specifics should not be extrapolated to other Sierra Nevada boulder-bedrock rivers without further and extensive study.

Example Pulse Flow Guideline	Hydrograph component	Justification
No. 1: Maintain the natural frequency and timing of unregulated 3-yr winter flood peaks up to the unregulated 15-yr winter flood peaks. Most will be short duration winter floods, but a few will be longer duration rainfall/snowmelt peaks in late winter or early spring. More than one flood peak can occur annually.	Winter floods, frequency and magnitude	No single magnitude or frequency of flood accomplishes all necessary geomorphic and woody riparian functions (Section 3.2.5 and 3.3.4). From an ecological perspective, low-frequency, high-magnitude floods (> 15-yr flood peaks) will happen, and should be encouraged. After a big flood, this pulse flow guideline will help perpetuate the big flood's benefits to the channel morphology and woody riparian plant community, rather than allowing/promoting a quick return to the channel's former impaired condition.
No. 2: Divert flows represented by the rising limb, peak, and fast recession limb of the unregulated annual snowmelt hydrograph, using a fixed percentage of the unregulated streamflow without significantly impairing the reference condition that emphasizes woody riparian initiation and early establishment, as well as sensitive life stages of selected fish, amphibians, and benthic macroinvertebrates. This study's preliminary analyses suggest maximum fixed daily diversion rates of 25% to 35%.	Snowmelt floods	An acceptable flow diversion rate during the snowmelt hydrograph period should cause as little divergence from reference conditions as possible, i.e., the reference condition curves should remain close to the 100% line. If an acceptable change in reference condition is +/- approximately 25%, then inspection of Figures 102 to 106 indicates that an acceptable daily diversion rate may range from 25% to 30%.
No. 3: Do not divert the snowmelt slow recession flows (i.e., those flows represented by the unregulated snowmelt hydrograph's slow snowmelt recession limb, starting at the point just past the annual snowmelt recession node).	Snowmelt slow recession flows	Elimination of the snowmelt hydrograph has been considered beneficial to rainbow trout (EA Engineering 1987), but that strategy purposefully deviates from the reference condition. While many feel that whatever helps trout helps the river ecosystem, the project's field study and analyses indicate otherwise. Adhering to Guideline No. 3 will result in "good with the bad" habitat conditions late into the snowmelt hydrograph period and into summer baseflows, and will keep reference conditions near 100%.

3.8. Uncertainties, Monitoring Opportunities, and Future Research Needs

As stated in the Introduction (Section 1.1), less research has been focused on steep boulder-bedrock rivers than on alluvial rivers. This study has deepened our knowledge of flow regulation effects on boulder-bedrock Sierra Nevada rivers, but many concepts need additional detail and further analysis. Some of these additional data needs and analyses are discussed below.

A network of photographic points or sites should be initiated, with specific purposes and hypotheses explicitly stated for each photo-point location. The temptation to first invest in hydraulic modeling and bed mobility prediction should be resisted, because existing photographic evidence contradicted modeling results, as in the lack of cobble and small boulder movement in narrow, confined mainstem reaches following 4.4-yr floods. A more theoretical approach would require more time, would undoubtedly cost more, and would still require verification with photographs.

If aerial photographs are taken, the contractor must be aware of the need to avoid shadows; in steep canyons, avoiding shadows can be problematic, but is essential if aerial photographs are to be useful. With additional funding, approximately $10,000 per river, periodic low elevation aerial photography along selected mainstem river segments (with stream gages) would be invaluable. These aerial photographs should be complemented with ground photography already recommended above.

A readily accessible hydrologic database, containing exact locations, dates, and flows, should be initiated in conjunction with the photo-point network. Construction of a flood timeline for the Clavey River was not as simple as first thought; a few years of missing water records (when the USGS gaging station at Buck Meadows was closed down) created uncertainty in the flow records.

The bed mobility methodology by Barta et al. (2000) can be improved so that it can better apply to the complex 3-D hydraulics of boulder-bedrock rivers. Presently, bed mobility predictions are reasonably accurate in alluvial gravel bedded streams, but next steps to improve the Barta et al. (2000) methods include: (1) adding more data for a wider variety of rivers, with a wider range of channel widths, slopes, and obstruction sizes, (2) evaluating whether to consider the deposit's lateral location within the cross section, which would move the emphasis of the strong gradient of boundary shear stress from the center of the channel to the margins, and (3) identifying more specific guidelines on what slope values to use. If bed mobility could be simply related to reach slope, obstruction size, and lateral location on the cross section, then these parameters may represent the primary sources of bed mobility. Particle size should also be additionally considered, but it may be less important than these three recommended improvements.

Deep pool stratification should be studied further, because it likely provides an important thermal refuge as the slow snowmelt recession flows transition into summer baseflows

(Section 3.5). Ambient water temperature in the approach riffle and deep in the adjacent downstream pool, coupled with daily streamflow measurement, would help identify streamflow thresholds that initiate pool stratification. This information could lead to a better ecosystem consideration of baseflows, rather than targeting some high weighted useable area (WUA) percentage for adult trout rearing habitat. Higher than unregulated baseflows may make the water slightly cooler, but might not compare to the significantly colder water in deep pools, assuming that augmented baseflows are low enough to promote stratification.

Water temperature should be given greater emphasis when evaluating instream flows. The up- and downstream movement of flow isotherms (the trombone effect) changes with water year type and timing and magnitude of flow releases. Because water temperature is strongly dependent on river mainstem shape and large depositional features, temperatures in side channels may be several degrees higher than mainstem streamflows. Shoaling upstream flanks of bars will also have warmer water temperatures than the adjacent flowing mainstem. Warmer water temperatures (but below stressful temperatures) during egg incubation and tadpole growth can mean larger individuals heading into the winter. These aspects of water quality, rather than the almost exclusionary focus on habitat availability or abundance, have not been given sufficient weight in evaluating instream flows.

Additional research into identifying water temperature thresholds is necessary. Copious water temperature data are of limited use if temperature thresholds have not been established for multiple life stages of organisms other than rainbow trout or brown trout. For this project, water temperature data were instrumental in identifying windows of habitat needs by different species and life stages. Water temperature thresholds for benthic macroinvertebrates were surprisingly difficult to locate; although benthic macroinvertebrates are diverse, general threshold criteria would be very useful even if only for the EPT species.

A geomorphic mobility threshold for pool *sweep-out* has not been identified. Pool sweep-out can occur during high streamflows, when bedrock pools experience hydraulic jumps that could very effectively remove large boulders. In surveying the Clavey River after several years of relatively low flows year-round, large boulders do not appear to collect in the bottoms of bedrock pools. In Cherry Creek, ”extra” boulders may be in the pools. Simple hydraulic modeling in a few pools and the placement (rolling-in) of large painted boulders for monitoring in gaged mainstem rivers would help identify the threshold of flood flows that sweep out pools.

An abbreviated study similar to this project should be performed in a drainage higher in the watershed, to study the effects of primarily snowmelt runoff on channel morphology and ecology. The Clavey River is situated at a transition from a snowmelt- to a rainfall-dominated hydrology, and the Clavey River study site is a recipient of both. Higher in the watershed, where snowmelt runoff almost entirely dominates the hydrology, the absence of winter flood peaks will likely affect channel morphology and ultimately the river ecosystem.

A study that allows validation of the expert habitat mapping should be designed. Field validation of any/all models used in this methodology would decrease the degree of uncertainty associated with this new methodology.

Further research into the literature of species thresholds is recommended. For example, temperature thresholds for some life stages of some species were difficult to obtain. Further research is also recommended to incorporate the latest findings of intermediate disturbance hypotheses into “good with the bad” reference conditions.

To identify an acceptable percentage of the snowmelt hydrograph’s daily diversion, the reference condition curve analysis was limited and was provided as one possible analysis that would still incorporate ranges of flows, rather than an optimum flow. Many physical and biological processes and habitat trends could be graphed on the same Y-axis, then compared to a number of diversion strategies represented on the X-axis. While the PHABSIM methodology for generating the weighted useable area (WUA) curves has been highly standardized, much less attention has been given to the use of WUA curves that do not depend on the optimum area. The reference condition curves might help, considering that they rely on similar information.

A next step is to apply this methodology to several existing and theoretical dam operations to evaluate their effects on hydropower generation and dependable water supply. Another ”next” step is to forecast the probable outcome of only partially satisfying the three example pulse flow guidelines. While most dam operations have the infrastructure to meet Guideline 3, the other guidelines are much more operationally difficult to follow. For example, releasing flood peaks less than the 15-yr flood, as recommended in Example Pulse Flow Guideline 1, may turnover spawning gravel for trout but can also exacerbate sand aggradation along the channel margins and further impair habitat for other species and trout fry rearing habitat.

4.0 Conclusions

4.1. Conclusions

The project study design addressed the four project objectives discussed in Section 1.2; each project objective was met (Table 28).

Table 28. Conclusions supporting the achievement of project objectives.

Objective	Conclusion and Referenced Report Section(s)
1. Quantify mobilization thresholds for depositional features and establish trends in species habitat availability. Both are dependent on the magnitude, duration, frequency, and timing of: (1) the annual snowmelt flow regime, and (2) winter peak floods, for a boulder sub-reach of the mainstem Clavey River.	Mobilization thresholds were quantified for four ranges of flood recurrences (Section 3.2.5). Trends in species habitat availability were established as functions of winter peak floods and snowmelt flows for two types of depositional features in the Clavey River: the boulder sub-reach and the Cottonwood Bar sub-reach (see habigraphs for all species).
2. Assess how altering flows could directly and indirectly affect habitat used by species of concern (Section 1.1.1). Effects would be assessed by linking variable annual snowmelt flows to physical depositional/scour processes, depositional/scour morphological features, water temperature, and life history timelines.	Species habitat area was further analyzed to determine the species ecologically available habitat, by considering desiccation and scour risks, water temperature and species temperature thresholds, and life stage windows (see habigraphs for all species). Risks of desiccation and scour were further analyzed for riparian trees, rainbow trout redds, and foothill yellow-legged frog metamorphosis (Sections 3.4.3; 3.4.4, subsection Rainbow Trout Redd Desiccation and Scour Risk; and 3.4.5, subsection Foothill Yellow-legged Frog Tadpole Metamorphosis Risk in Depositional Features).
3. For a regulated Sierra Nevada boulder-bedrock river ecosystem, demonstrate that: (1) variable winter and snowmelt pulse releases designed to re-create and maintain specific geomorphic and ecological thresholds can improve many aspects of the river ecosystem, and (2) impounding flow such that annual snowmelt flows and winter peak floods are altered or eliminated can allow geomorphic and ecological responses to be forecasted. Given the results of these demonstrations, formulate example pulse flow guidelines.	The case for variable winter floods and snowmelt flows is presented by considering the implications of this study's synthesis (Section 3.6). The geomorphic and biologic roles of natural winter and snowmelt floods are described. To the extent that released pulse flows can mimic variable timing and magnitudes of winter and snowmelt floods, then geomorphic and ecological responses can be predicted. After defining reference conditions and declaring them to be ecological goals, example pulse flow guidelines were formulated (Section 3.7).
4. Highlight and evaluate uncertainties in the project's outcomes, recommend changes in field data collection and analytical procedures, recommend future sampling and analyses, and identify further information needed to quantify nested geomorphic thresholds, species habitat, and life history requirements that are relevant to winter floods and annual snowmelt flows.	Several areas of uncertainty could be better defined with further research (Section 3.8). Better photographic information (in lieu of hydraulic and bedload mobility modeling) would be useful in future research. Water temperature and species temperature threshold data could be better defined. Improvements to Barta et al. (2000) methods are described. Finally, a more thorough examination and

Objective	Conclusion and Referenced Report Section(s)
	validation of reference condition curves would be useful in better formulating pulse flow guidelines.

4.2. Benefits to California

The project provides a preliminary test of a methodology for formulating numeric pulse flow guidelines. To promote recovery of native Sierra Nevada river ecosystems, the guidelines could be used to determine which existing dam operations have the infrastructure required to release flows that follow the guidelines. Small capacity reservoirs that can pass winter flood peaks up to the 15-yr flood, with or without infrastructure upgrades, would be good candidates for river ecosystem recovery. While there are many demands on any given operation, river ecosystem recovery should be attempted in places with the best chance of success.

The project demonstrates that flushing flows to periodically mobilize spawning gravel at pool tails or planned flood releases that target the 1.5-yr flood, often called the *bankfull discharge,* will not maintain a variable mainstem channel architecture; therefore, flushing flows will not maintain a river system of diverse species.

In many regulated Sierra Nevada rivers, loss of the snowmelt peak and recession flows must be acknowledged when a river ecosystem management perspective is claimed. This project demonstrates that snowmelt peak and recession flows are not primary geomorphic forces, but they are as important as large magnitude winter floods in maintaining river ecosystems.

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6.0 Glossary and Acronyms

Glossary

Word or phrase	Definition
Alevins	Life stage of salmonids starting when eggs hatch. The larvae or alevins remain in the gravel for two to three weeks, emerging 30 to 50 days (or more) after fertilization depending on water temperature.
Available habitat area	Habitat area (ft^2) quantified by expert habitat mapping as a function of daily average streamflow.
Biological hotspots	These areas are short channel segments that support unique and/or diverse aquatic and riparian communities, typically occurring in reaches that are highly depositional.
Annual hydrographs	Annual hydrographs are plots representing flows over time. They can be characterized by their variations in flow magnitude, duration, frequency, and timing, and they can be categorized into water year types. Further, annual hydrographs can be partitioned into discrete hydrograph components, including winter storm events, winter and summer baseflows, spring snowmelt peaks, and spring-summer snowmelt fast/slow recession limbs.
Complex	In the context of benthic macroinvertebrate habitat mapping, *complex* refers to hydraulically complex.
D_{84}, D_{50}, and D_{31}	The particle diameter at which x% of the sampled particles is smaller, where x is typically 84%, 50%, or 31%.
Ecologically available habitat area	Each day's habitat in a given species/life stage habigraph that: (1) occurs within the time period for that life stage, (2) falls within the favorable temperature range, and (3) is relatively abundant.
Expert habitat mapping (EHM)	A methodology in which biologists quantify the area of good habitat by mapping it directly in the field.
Habitat rating curves	Graphical representation of mapped habitat area and daily average streamflow for a given species and life stage.
Habigraphs	A graphical representation, combining species habitat rating curves with snowmelt hydrographs, portraying the amount of available habitat (ft^2 of habitat on the Y axis) on any given day during the snowmelt hydrograph of a given runoff year (day on the X axis).
Hydrograph	See annual hydrograph.
Phenology	The study of regularly recurring biological phenomena such as animal migrations or plant budding, especially as influenced by climatic conditions.
Pilot study	An initial study that precedes an in-depth and detailed study.
Pool sweep-out	The occurrence of gravel being removed from a pool during high flows.
Reference condition	The number of days in a particular runoff year's habigraph in which ecologically available habitat occurs under unregulated streamflows for a specific species and life stage.

Word or phrase	Definition
Reference condition curves	The computed reference condition expressed as a percentage, the number of qualifying days in the unregulated habigraph as the denominator and the number of qualifying days in a habigraph created under a specific managed snowmelt hydrograph as the numerator, plotted as the percent reference condition on the Y axis and the daily fixed diversion rate on the X axis.
Runoff year	A runoff year is a subset of the 12-month water year, and covers from March 20 through August 10 targeting the snowmelt runoff season.
Snowmelt hydrograph	A hydrograph that represents flows over time, but focusing on the snowmelt period from April 1 to August 31.
Snowmelt recession node	On a snowmelt hydrograph, a distinctive feature of the snowmelt recession limb is a break in slope, transitioning from a rapidly declining recession limb to a more gentle recession limb. The flow at which this transition occurs is called the *snowmelt recession node.*
STA X + Y *(example: STA 29+30)*	Cross section identifier that indicates the cross section station is located 2930 feet upstream from the confluence point of the tributary and its mainstem.
Stage-o-graph	Graphical representation of the snowmelt flow's surface elevation (relative to the thalweg elevation) over time on a stream cross section.
Trombone effect	Occurrence of a stream isotherm that moves up- and downstream.

Acronyms and Abbreviations

Acronym or abbreviation	Complete name
CDFG	California Department of Fish and Game
cfs	cubic feet per second
EHM	Expert habitat mapping
HEC-RAS	Hydrologic Engineering Centers River Analysis System, developed by the U.S. Army Corps of Engineers
HVT	Hoopa Valley Tribe
PHABSIM	Physical Habitat Simulation Model
PIER	Public Interest Energy Research Program, formed by the California Energy Commission
RM	River mile
RY	Runoff year
SL	Standard length
SNTEMP	Stream Network Temperature Model, by the U.S. Fish and Wildlife Service
STA	Station
TID	Turlock Irrigation District
USFS	United States Forest Service
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WUA	Weighted usable area
WY	Water year

Appendix A
Attributes of Steep Boulder-Bedrock Sierra River Ecosystems

Appendix A
Attributes of Steep Boulder-Bedrock Sierra River Ecosystems

To define a common vision of the characteristics of unregulated steep, boulder-bedrock rivers, important characteristics or endpoints of any management strategy must be agreed upon. Seven characteristics, or attributes, of unregulated, steep, boulder-bedrock rivers have been described elsewhere (McBain and Trush 2004) and were analyzed and applied to the Clavey River. A summary of that analysis was presented in the main report's Section 1.1.1. This appendix is a more detailed version Section 1.1.1.

Attribute 1. Steep boulder-bedrock Sierra Nevada rivers exhibit nested depositional features.

> Boulder-bedrock channels, though principally erosional, exhibit abundant depositional features. Large geomorphically derived hydraulic controls, such as valley width constrictions or expansions and resistant bedrock outcrops, define an overall limit for coarse sediment deposition in each segment of bedrock channel. These geomorphic controls induce coarse depositional features that in turn perform as smaller hydraulic controls inducing finer secondary depositional features. Transverse boulder 'ribs' are prominent self-formed depositional features common in bedrock Sierra Nevada rivers that function as hydraulic controls for diverse secondary, and even tertiary, depositional features. The occurrence of smaller hydraulic controls within larger hydraulic controls gives rise to a complex, nested depositional channel morphology that provides rich aquatic and riparian habitats (McBain and Trush 2004).

At first glance, a boulder-bedrock Sierra river appears to be a chaotic collection of large and small boulders with an occasional bedrock pool. Attribute 1 asserts something orderly underlies the chaos: nested hydraulic controls. An *hydraulic control* is a prominent roughness element (e.g., a large boulder or bedrock outcrop) or channel characteristic capable of modifying the local water surface slope and inducing scour or deposition. During rising flows of a large flood, a cluster of basketball-sized boulders functioning as a hydraulic control for a small sandy lee deposit can be drowned out by a larger hydraulic control, such as downstream rib of 7-ft diameter boulders. Hydraulic controls, therefore, are typically nested (Figure A-1). Primary hydraulic controls (such as constricting bedrock valley walls) are capable of influencing the water surface slope and hydraulics of major floods. Secondary hydraulic controls may be drowned out during a major flood, but are capable of influencing water surface slopes and hydraulics of smaller floods. These secondary hydraulic controls, and even smaller tertiary hydraulic controls, lie within the influence of larger hydraulic controls and are therefore nested.

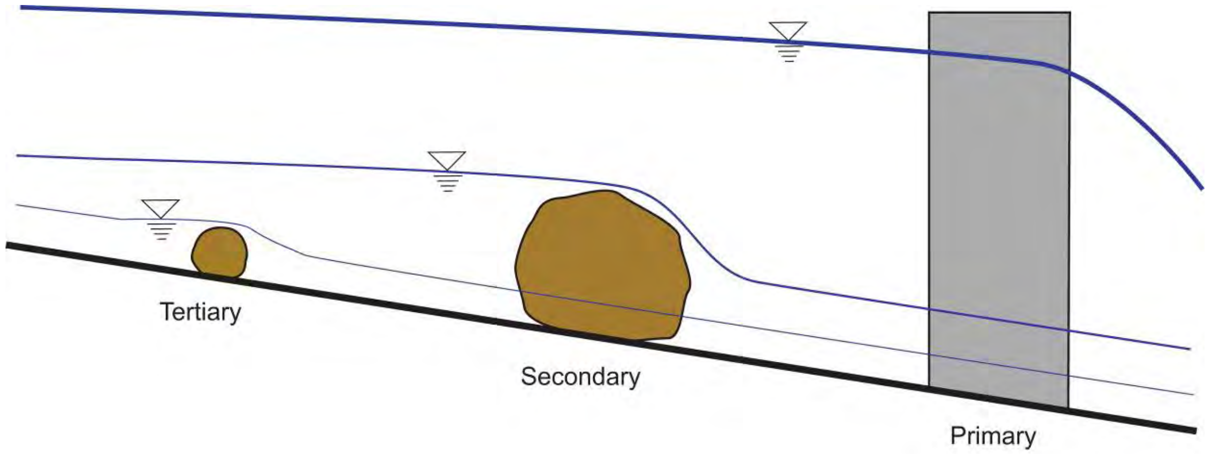

Figure A-1. An idealized segment of a boulder-bedrock channel with three levels of nested hydraulic controls and associated depositional features

Primary, secondary, and tertiary hydraulic controls will create depositional features, if bed material is being actively transported when local hydraulics favor deposition (Figure A-2). A string of boulders spanning the channel can influence water surface slope during flooding and induce downstream or upstream deposition when coarse sediment is actively being transported. A sharp constriction of opposing bedrock valley walls can create a backwater at very high flood flows to force a large point bar upstream or induce a hydraulic jump to shape a deep pool downstream.

Nested hydraulic controls create nested depositional features. The end result, the geomorphic chaos seen in the channel, is a hydraulically complex channel sustaining a diversity of depositional features (Figure A-3). Large-scale depositional features (boulder ribs, forced point bars comprised of boulders) are infrequently shaped by primary and secondary hydraulic controls during big floods, while smaller-scale depositional features (gravel and cobble deposits in the lee of boulders) associated with small secondary and tertiary hydraulic controls are scoured and reshaped by frequent small floods. Large-scale depositional features, such as a rib of car-sized boulders deposited upstream of a valley constriction during a 150-yr flood, can act as a secondary hydraulic control, inducing formation of a cobble point bar upstream.

Each hydraulically nested level occupies a unique position in a spatial and temporal continuum. Primary hydraulic controls function on the geologic end of the continuum, whereas most tertiary hydraulic controls function at the opposite end, well within a human's momentary lifespan and typically at a spatial scale less than 100 ft^2. Attribute 1 tells us that whatever happens today happened because of what happened yesterday and several million yesterdays. For example, a gravel deposit used for spawning may be the direct result of deposition in the lee of a boulder. But just as necessary for spawning was the boulder's transportation from its ultimate source and its fluvial arrangement among other boulders. While recognition of this broad continuum may be informative and "tells a good story," it has immense practical application as well.

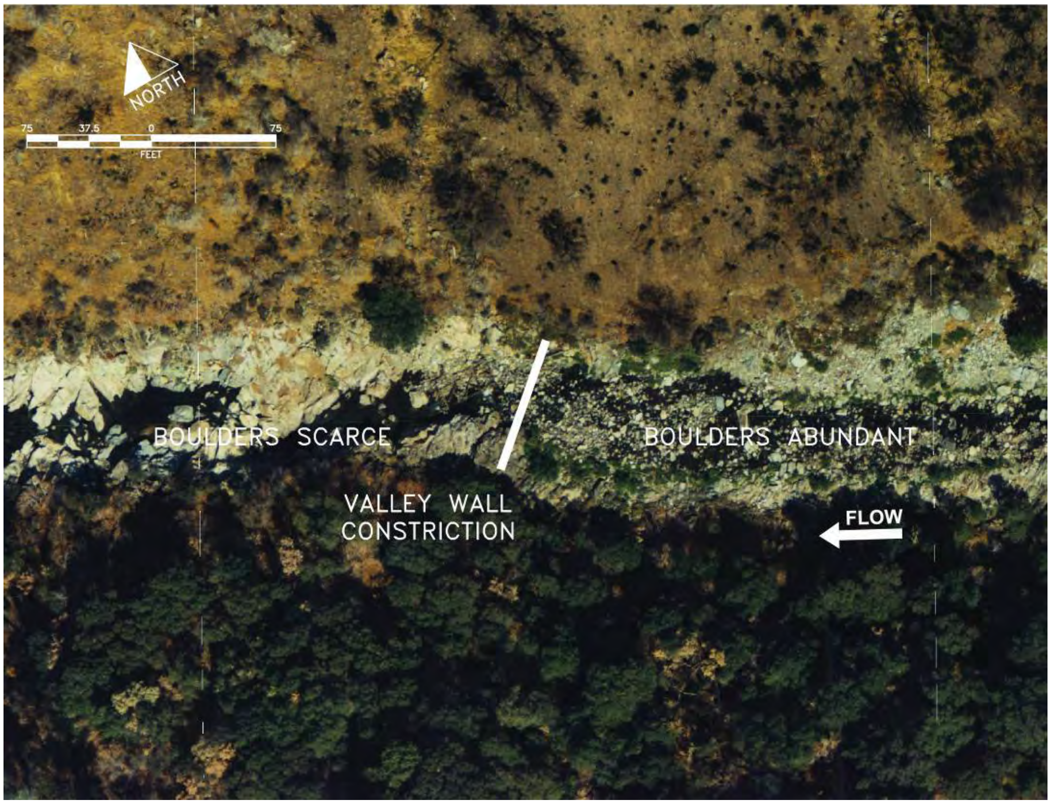

Figure A-2. Example of a valley wall constriction functioning as a primary hydraulic control. Note the presence of abundant boulders upstream of the constriction but their absence downstream. Photograph taken downstream of the 1N01 Bridge on the mainstem Clavey River, August 1988.

River managers can accept primary hydraulic controls as being static (perhaps a huge landslide spanning the river channel would be an exception) and attempt to manage smaller, more dynamic hydraulic controls to create and sustain depositional/scour features just as unregulated rivers do. Pulse flows, therefore, can be management tools that allow nested hydraulic controls to create, shape, and sustain diverse depositional features. A classification scheme for defining depositional features was crafted for the project to synthesize experimental findings and to recommend streamflow thresholds that shape and scour these features.

Attribute 2. Boulder-bedrock river ecosystems require variable annual hydrographs.

> Annual hydrographs can be partitioned into discrete annual hydrograph components (including winter storm events, winter and summer baseflows, spring snowmelt peaks, and spring-summer snowmelt recession limbs), each characterized by variation in flow magnitude, duration, frequency, and timing among different water year types. Each annual hydrograph component uniquely (a) contributes to geomorphic processes that shape and maintain depositional and erosional features, (b) sustains varied life history and habitat requirements for those plant and animal

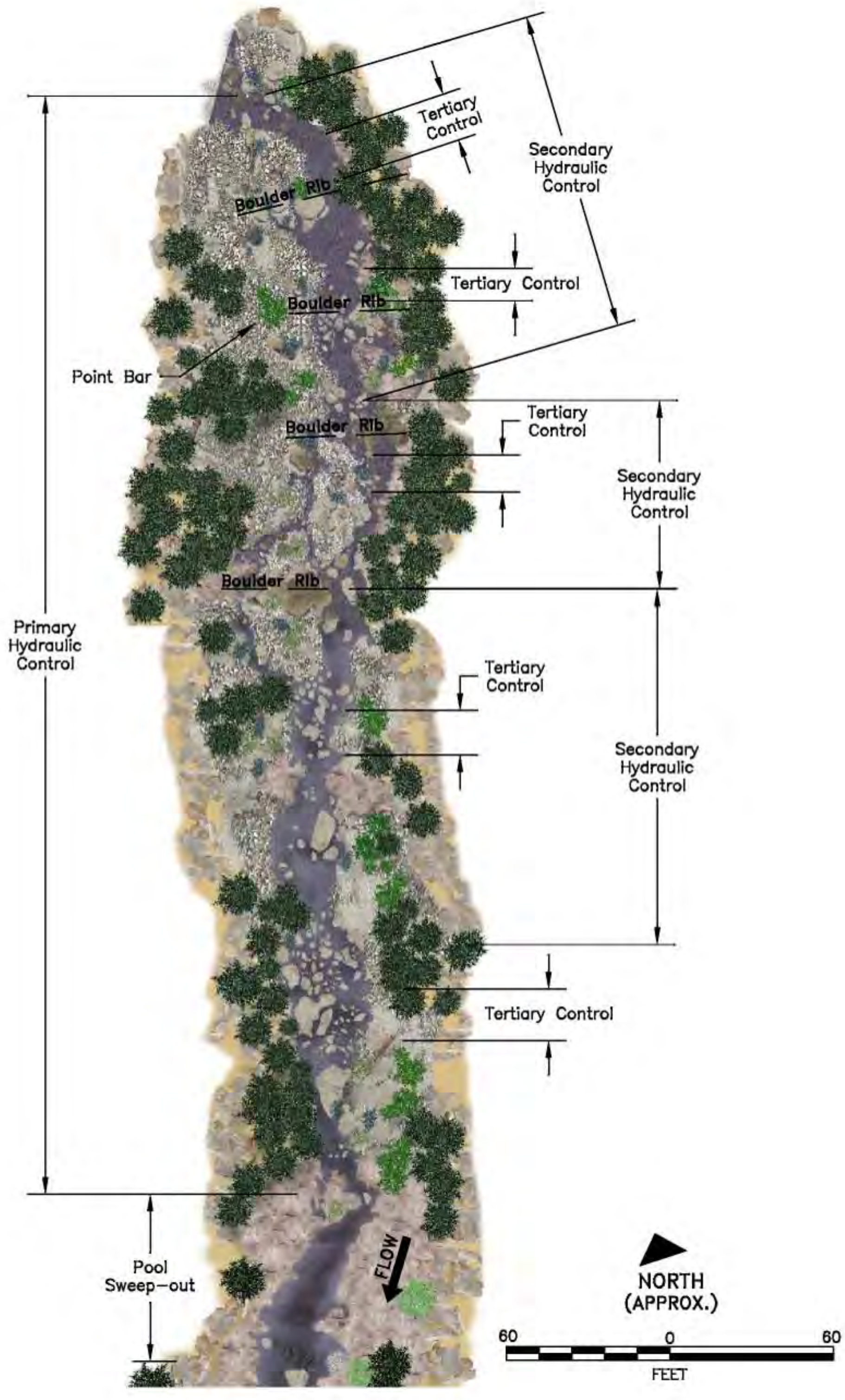

Figure A-3. Stylized aerial photograph of nested hydraulic controls and depositional features within one channel reach of the Clavey River

species native to bedrock Sierra Nevada river ecosystems, and (c) perpetuates early-successional woody riparian communities. (McBain and Trush 2004)

A hydrological description of streamflows in Sierra Nevada river ecosystems must (McBain and Trush 2004): (1) faithfully describe natural variation in flow magnitude, duration, frequency, and timing within and among different types of water years, (2) relate directly to geomorphic flow thresholds and life history requirements of native species and communities, and (3) encourage manageable flow prescriptions in regulated rivers. Using annual hydrograph components to describe annual flows, while not perfect, meet these criteria. Hydrograph components for a rainfall-snowmelt hydrologic regime typical of Sierra Nevada rivers includes winter storm peaks, winter and summer baseflows, snowmelt peaks, and snowmelt rising and recession limbs (Figure A-4).

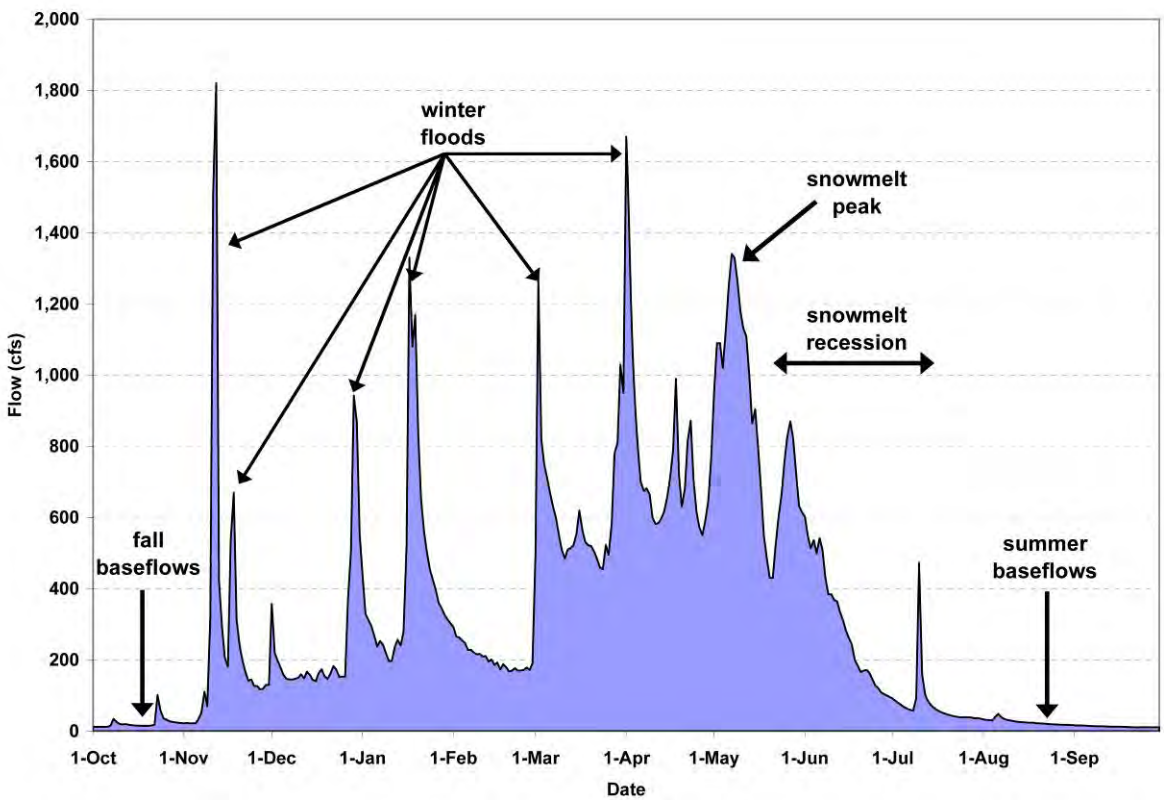

Figure A-4 Annual hydrograph components in WY1979 for the Clavey River at Buck Meadows USGS Gaging Station No. 11283500

Pulse flows can be considered managed annual hydrograph components with one distinction. A snowmelt pulse flow is the entire snowmelt hydrograph composed of three annual hydrograph components: a steep rising limb, a sustained peak flow, and a two-stepped recession limb. Although winter floods also have rising and receding limbs, both extremely steep, the peak magnitude of the winter flood is of most interest as a flow threshold for mobilizing depositional features, scouring pools.

The magnitude, duration, and timing of winter and snowmelt floods are unique every year, but roughly vary by water year type. Consequently, the extent of geomorphic work accomplished will differ one year to the next. A major peak snowmelt flood characteristic of wet water years can scour gravel and cobbles from the surface of a prominent point bar, but a much lower peak snowmelt flood characteristic of a dry water year may not even inundate the same point bar. The natural occurrence of water year types, therefore, reflects the natural annual variability of geomorphic work accomplished.

While the geomorphic role of peak magnitude floods has been emphasized in winter and snowmelt floods, the rising and receding limbs of the snowmelt hydrograph (as well as the peak) can strongly influence habitat quantity, habitat quality (e.g., water temperature), and life history timing for all native species. An extended snowmelt recession limb into late July or even early August, characteristic of wet years, will keep water temperatures cooler longer and certain depositional features inundated longer. The natural occurrence of annually variable snowmelt runoff periods produces annually variable habitat quality and quantity. Seasonally dependent life history requirements, such as the short timespan when many riparian plants are dispersing viable seeds (often as short as two weeks), have evolved to the natural timing and frequency of the snowmelt runoff period.

Attribute 3. Episodic sediment delivery enhances spatial complexity.

> Hillslope mass wasting, such as rock falls and bedrock shearing from canyon walls, episodically deliver colluvium of sufficient volume and/or caliber that create large depositional features in the channel or function as large-scale hydraulic controls capable of generating other prominent depositional features. (McBain and Trush 2004)

Episodic events can leave geomorphic signatures on channel morphology. They can impose hydraulic controls anywhere. The high transport capacity of highly confined bedrock channels has tremendous power to modify a huge debris slide blocking or constraining the mainstem channel (as occurs in the lower mainstem Clavey River). The intervening period while the slide feature remains may be brief geologically but extended biologically, supplying a unique depositional environment. Attribute 3 stresses the need for continued (unimpeded) episodic events to promote their somewhat rare brand of geomorphology that contributes disproportionately to complex channels and ultimately diverse river ecosystems.

Attribute 4. Boulder-bedrock channel maintenance requires multiple flow thresholds.

> Multiple flow thresholds must be met to maintain erosional and depositional features of bedrock channels by initiating diverse depositional and erosional processes. Infrequent large "re-setting" floods (approximately 25-yr annual maximum floods and greater) are needed to: (a) significantly scour and redeposit large depositional features such as entire lateral bars, (b) reposition and aggregate large boulders into depositional features such as transverse boulder ribs, (c) periodically remove mature woody vegetation from bars and along channel margins, (d) encourage avulsions in broader channel reaches, (e) prevent steepening

> of riffles due to excessive boulder accumulation, and (f) sweep-out boulders accumulating in bedrock pools. More frequent, lower magnitude floods (10-yr to 20-yr annual maximum floods) are needed to (g) significantly mobilize surface layers of large coarse-grained bars in part to minimize woody riparian encroachment, (h) deposit smaller coarse depositional features associated with transverse boulder ribs and/or individual large boulders and bedrock outcrops, and (i) deposit silt and sand on floodplains and low terraces. Frequent snowmelt flood hydrographs (up to 5-yr annual maximum floods having relatively small peak discharges) are needed to (j) maintain a high turnover of fine-grained depositional features (composed of small cobbles and finer particles) often associated with secondary hydraulic controls of bars and transverse boulder ribs, but also in gravel deposits of bedrock pool tails (e.g., spawning habitat for salmonids, and (k) build limited floodplains. (McBain and Trush 2004)

Russell (1902) noted that for steep bedrock Sierra Nevada rivers "one of the most important principles connected with stream transportation is that flowing water assorts the debris delivered to it." The first three attributes, which set the stage for how flowing water sorts sediment (debris) in bedrock channels, are integrated by Attribute 4. It takes the nested hydraulic controls and depositional/scour features of Attribute 1, submits these controls and features to variable hydrograph components through Attribute 2, and supplies the unpredictable (but certain to occur) wild card of Attribute 3. All three are needed to meet the physical demands of a complex boulder/bedrock channel morphology. Attribute 4 makes intuitive sense: no single pulse flow could be expected to maintain the morphologically diverse erosional and depositional environment of boulder-bedrock Sierra Nevada rivers.

Attribute 5. Maintenance of depositional features is mostly independent of the coarse bedload transport capacity.

> Bedrock rivers have a huge, and generally unfulfilled, potential transport capacity for coarse sediment, but a low temporary storage capacity of coarse and fine sediment comprising all depositional features. Hydraulic complexity and channel form, expressed as nested hydraulic controls in a variable flow regime, exert the greatest control on storage capacity. The annual coarse bedload transported may fluctuate significantly without affecting the volume of coarse sediment stored in a channel segment. Although storage capacity is low, the ecological implications for maintaining even limited depositional features are great. (McBain and Trush 2004)

Boulder-bedrock channels can transport coarse sediment well in excess of the actual sediment supplied. As Russell (1902) observed: "Not only do they [Sierra Nevada rivers] bear away all of the fine material that reaches them, but in times of high water roll along large boulders, and yet their capacity to transport is not satisfied." Complex hydraulics and channel morphology, expressed as nested hydraulic controls in a variable flow regime, establish the storage capacity for coarse sediment. Thus the annual coarse bed material supplied to a channel segment may fluctuate significantly without seriously affecting the volume of coarse sediment stored in that channel segment.

Attribute 6. Biological hotspots occur at highly depositional channel reaches.

> Biological hotspots, short channel segments supporting unique and/or more diverse aquatic and riparian communities, typically occur where the local river corridor or major episodic geomorphic events exert large-scale hydraulic control over deposition. These atypical channel segments exhibit prominent depositional features, and even alluvial tendencies such as limited floodplains, that are highly dependent on snowmelt flood and recession hydrograph components. (McBain and Trush 2004)

River ecosystems rely on hydraulic controls. Biological hotspots, which are relatively rare channel segments supporting unique and/or more diverse aquatic and riparian communities, typically occur where the local river corridor or major episodic geomorphic events exert primary hydraulic control over deposition. Attribute 6 may be the most compelling reason for wanting to manage boulder-bedrock river ecosystems ecologically. These atypical channel segments exhibit many prominent depositional features, including aggradational floodplains. This depositional tendency promotes smaller particle sizes, abundant riparian habitat, off-channel amphibian habitat, early life history habitat for fish, and higher overall biological diversity. Biological hotspots result from all other attributes and serve as constant reminders that nature is attracted to novelty.

Attribute 7. Hydrologic pathways in the river corridor fluctuate seasonally and annually.

> Variable hydrograph components, particularly the snowmelt recession limb and baseflows, sustain hydrologic pathways throughout the river corridor. (McBain and Trush 2004)

The magnitude, duration, and timing of the annual snowmelt pulse flow can greatly influence water availability in prominent depositional features. The simplicity of stating Attribute 7 underlies how little this role has been understood, and consequently appreciated.

References

McBain, S. M., and W. J. Trush. 2004. Attributes of bedrock Sierra Nevada rivers. *Stream Notes.* U.S. Forest Service Stream Technology Center, Rocky Mountain Research Station. Ft. Collins, Colorado. January. 4 p.

Russell, I. C. 1902. T*he Progressive Science Series: River Development as Illustrated by the Rivers of North America*. John Murray Publishers, London.

Appendix B
Depositional Feature Classification

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Depositional Feature Classification

A classification scheme for defining depositional features in steep boulder-bedrock rivers (Table B-1) was a handy tool for systematically investigating geomorphic streamflow thresholds. Ten types of depositional features were observed in the Clavey River between the 1N01 Bridge and 1N04 Bridge, but this classification would equally apply to Cherry Creek. All of these features have been described in the scientific literature, although often under different names.

Table B- 1. Depositional features in steep, boulder-bedrock Sierra Nevada rivers

Depositional Feature	Definition of Depositional Feature	Example Photograph
Aggraded Floodplain	An almost flat or gently sloping surface (away from the thalweg) typically associated with a point bar and created by progressive overbank deposition of silt and sand	Figure B-1
Boulder Rib	Boulders arranged in a transverse line spanning the channel	Figure B-2
Point Bar	A large-scale depositional feature, with a length approximately equal to the length of the top or bottom half of the “S-shaped” curve of the channel. The S-shaped channel is assumed to have a relatively short radius of curvature, and the thalweg is located toward the outside bank. Coarse bedload is transported across the point bar surface rather than along the channel thalweg	Figure B-3
Lateral Bar	Cobble and small boulder deposits sheltered from large floods by bedrock protruding from the valley wall or large boulders protruding from the riverbank	Figure B-4
Boulder Cluster	Collection of boulders, two or more, each in physical contact with one another	Figure B-5
Lee Deposit	Accumulation of fine/coarse sediment immediately downstream of a roughness element, commonly a single boulder or boulder rib, with the deposit’s surface sloping negative, that is, toward the channel bed	Figure B-6
Obstruction Deposit	Accumulation of fine/coarse sediment upstream of a roughness element, commonly with the deposit’s surface sloping steeply positive, that is, toward the surface	Figure B-7
Perched Deposit	Accumulation of fine/coarse sediment in local depressions formed by coarser particles or bedrock that is elevated above the thalweg, commonly with the deposit’s surface slope appearing flat or reflecting a high flow slope	Figure B-8
Pool/Run Tail Deposit	Fine/coarse sediment deposited at or near a pool or run’s downstream control at baseflow stage, with its surface generally ramping upward	Figure B-9
Eddy Deposit	Fine sediment deposited during late stages of falling flood limb	Figure B-10

Note that a particular type of depositional feature may be associated with more than one level of hydraulic control. A pair of small boulders (the simplest of boulder clusters) deposited in front of (and because of) a boulder rib can function as a tertiary hydraulic control responsible for a small gravel obstruction deposit. Car-sized boulders stacked upstream of sharply constricting bedrock walls also would be a boulder obstruction deposit, but created by a primary hydraulic control.

Floodplains and Aggraded Floodplains (Figure B-1)

Usually associated with alluvial rivers, aggraded floodplains are present on the Clavey River in wide mainstem segments. Cottonwood Bar on the Clavey River has an aggraded floodplain of deposited silt, sand, and gravel greater than 200 ft at its widest, topped by 0.5 ft of organic matter. Unlike alluvial rivers, where the floodplain might be inundated by a 1.5-yr to 2-yr flood, this aggraded floodplain was almost inundated by a 75-yr flood in 1997. No evidence of debris jams, woody debris wrapped around the trunks of the mature conifers, or flood scarring on the trunks indicated recent significant flooding (flow roughly 2- to 3-ft deep on the floodplain surface) occurred within the lifetimes of mature conifers (> 150 years). However, the trace of a former side-channel thalweg, near the right valley wall, was evident. The migration rate of the point bar associated with the aggraded floodplain is extremely slow, causing the original floodplain surface to aggrade when overtopped by the largest floods. Therefore as time passed, each increment of aggradation required an even larger flood to continue floodplain deposition.

The narrow transition zone between the point bar and aggraded floodplain (Figure B-1A), the true floodplain, is inundated much more frequently. The 5-yr flood peak in 2005 deposited over 1 ft of sand along this transition zone in many locations. Flood debris stacked against conifers just behind the cross section tape in the center of Figure B-1B was left by the 2005 flood. Annual maximum floods of 2-yr to 3-yr begin to inundate this transition zone, i.e., at a frequency similar to alluvial channels. This transition zone may be the classic floodplain common in alluvial rivers. The aggraded floodplain surface begins approximately 30 ft back from the bright red engineer's level, then extends to the right bank valley wall. The 75-yr flood in WY1997 reached approximately 2 ft up on the tripod's leg of the bright orange engineer's level in Figure B-1B, but did not reach the aggraded floodplain surface. A side channel that flows only during wetter snowmelt hydrographs and winter floods separates the point bar from the true floodplain.

Figure B-1A and B. (A) Narrow floodplain as a transition from point bar to aggraded floodplain looking upstream from approximately midway on Cottonwood Bar in the Clavey River, with the point bar just off the photograph to the right and aggraded floodplain at upper far left of photograph (photographed May 27, 2005). (B) Aggraded floodplain, adjacent to Cottonwood Bar, in upper right half of photograph.

Boulder Ribs (Figure B-2)

Transverse lines of boulders spanning the channel, and that are arranged as "ribs," have been termed "boulder ribs" or "boulder sets." Boulder ribs in the Clavey River mainstem often occurred in sequences and at widely different spacings. Generally boulder ribs were closely spaced (at distances less than the channel width) in steeper and straighter channel reaches. In lower gradient reaches, boulder ribs were often widely spaced (spaced wider than the channel width). Steeper channel sections tended to have boulder ribs composed of larger boulders. The boulder ribs in Figure B-2 are functioning as secondary hydraulic controls at higher streamflows, as seen by the sharp changes in water surface elevations above and below the ribs, but cease to be secondary hydraulic controls at lower streamflows.

Point Bars (Figures B-1 and B-3)

Point bars can be larger-scale depositional features usually half a channel meander wavelength long[4] with a relatively short radius of curvature, where the thalweg is located toward the outside bank and coarse bedload is transported across its surface rather than along its thalweg. Cottonwood Bar is a large point bar with a prominent downstream bedrock hydraulic control (Figure B-1). Several boulder ribs radiate from the bar's inside bend. Point bars can also be small (Figure B-3). These are generally no longer than the channel is wide, but with the thalweg prominently located toward the opposite bank.

Large depositional features, such as Cottonwood Bar, are not common in the Clavey River mainstem. Large-scale depositional features, typically point bars and lateral bars, were inventoried for the mainstem Clavey River where there was good aerial photographic coverage, RM 17 to RM 8, for a comparison the project study site (RM 16.5 to RM 17.0). Depositional features were identified using a combination of 1:2400-scale black-and-white, non-stereo aerial photographs taken in 1988 and 1:6000-scale color stereo pairs taken in 1993. Deposits were identified on the 1993 photographs using a portable mirror stereoscope with 3x magnification and mapped onto laminated photocopies of the 1988 1:2,400-scale photographs. Mapped polygons were digitized on-screen over a 1993 USGS Digital Orthophoto Quad because there was no accurate way to georeference and register hard-copy maps or photographs to a digitizing tablet. A centerline was digitized through each polygon to calculate feature length and through the channel to calculate total channel length.

Thirty-four bar-scale deposits were identified between RM 8 and RM 17. Of these, 32 were located in channel bends and two at tributary deltas (at Reed Creek and an unnamed tributary). Mainstem bar deposits comprised 27% of the mapped channel length (Table B-2).

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[4] A channel meander is the characteristic "S-shape" of a stream channel. Point bar lengths are generally equal to the length of the top or bottom half of the "S-shaped" curve of the channel.

Figure B-2. A large upstream boulder rib (anchored on right bank bedrock outcrop) and small downstream boulder rib of modest 4- to 6-ft diameter boulders acting as upstream hydraulic controls on July 8 and May 27, 2005, in the mainstem Clavey River

Figure B-3. Small right bank point bar between widely spaced boulder ribs on XS 32+62 in the boulder-bedrock sub-reach of the mainstem Clavey River (streamflow right to left). Note: (1) the pronounced imbrication of boulders within the point bar, (2) the obstruction bar of small boulders piled against the flat, imbricated large boulder in the left foreground, and (3) beginning upstream, the bar surface slopes upward, then back down to low flow surface (photographed August 30, 2005).

Table B- 2. Large-scale depositional features in the Clavey River mainstem from RM 8 to RM 17

Parameter	Point/Lateral Bars n = 32		Tributary Deltas n = 2	
	area (ft^2)	length (ft)	area (ft^2)	length (ft)
Mean	15,882	344	17,172	703
Standard deviation	13,542	150	10,134	484
Total	508,239	11,002	34,344	1,405
% of total channel length	--	24%	--	3%

Roughly a quarter of the mainstem channel inventoried had large-scale depositional features such as point and/or lateral bars. However, this segment of the entire mainstem channel is less confined and less steep than other mainstem segments, and therefore more conducive to bar formation. With aerial photography of the quality needed to inventory channel features nonexistent for other mainstem segments, the percentage of the entire Clavey River mainstem channel length with large depositional features would likely decrease (from 20% down to 15%), based on observations and discussions with those familiar with the mainstem river from the USGS gage down to the Tuolumne River.

Lateral Bars (Figure B-4)

Gravel, cobble, and small boulder deposits are sheltered from large floods by bedrock or unusually large boulders protruding from the valley wall. These bars likely result from deposition during a single large flood, with subsequent smaller floods depositing smaller particles on the surface. These deposits might occur on the inside of a channel bend, making them similar to point bars. However, the bar surfaces generally slope gently downstream, unlike point bars that typically have a convex appearance. The mainstem thalweg can be practically anywhere, near either bank or down the centerline, whereas point bars generally are located on the inside of a bend and opposite the thalweg.

Figure B-4. Lateral bar along mainstem Clavey River just upstream of the Cottonwood Creek confluence looking downstream at a lateral bar. Bar is located on the inside of a channel bend and downstream of prominent boulders. Photographed September 3, 2005.

Boulder Clusters (Figure B-5)

Boulder clusters are associations of boulders, two or more in each association, where each boulder modifies the hydraulics of the others during baseflows but act together to influence their depositions at much higher streamflows. In many cases, a boulder cluster can function as a "seed" that will induce finer deposition (i.e., function as a tertiary hydraulic control). Boulder clusters are commonly found between widely spaced boulder ribs and long runs in large point bars.

Figure B-5. Boulder cluster in mid-channel of mainstem Clavey River (just to the left of the photograph's center). Photographed September 3, 2005.

Lee Deposits (Figure B-6)

Accumulation of fine and coarse particles downstream of a roughness element, usually a boulder and commonly with the deposit's surface, sloped downward in the downstream direction. Surfaces particles were sorted, and often had a distinct layer of fine sediment overtopping a much coarser subsurface.

A.

B.

Figure B-6. (A) Lee deposit along mainstem Clavey River upstream of Cottonwood Creek confluence, and (B) looking toward the right bank at the same lee deposit (streamflow right to left). Note that the bar surface slopes downward going downstream. Photographed August 30, 2005.

Obstruction Deposits (Figure B-7)

Accumulation of coarse particles (usually larger than small cobbles) upstream of a prominent roughness element (e.g., a boulder) was observed. Commonly, the deposit's surface slopes upward sharply in the downstream direction. Obstruction deposits are often associated with, and formed by, boulder ribs. These deposits tended not to be well sorted, especially relative to the sorting of lee deposits.

Perched Deposits (Figure B-8)

Accumulation of fine or coarse sediment in local depressions formed by boulders or bedrock elevated above the thalweg. The most obvious perched deposit observed was coarse sand in bedrock depressions typically 10 ft or more above the thalweg. Lenses of gravel on cobble and small boulder point bar surfaces also could be considered perched deposits.

Pool/Run Tail Deposits (Figure B-9)

Gravel and cobble deposits at or near a pool or run's downstream stage control baseflow, generally sloping gently upward (in the downstream direction) and generally less than the downstream control elevation. Occasionally, these deposits can become entire bar features (i.e., elevated above the pool's downstream hydraulic control at baseflow), especially on the downstream end of wide but short pools located immediately downstream of a straight steep channel segment (e.g., a long cascade).

A.

B.

Figure B-7. (A) Obstruction bar of coarse gravel and small cobble along the right bank mainstem Clavey River on XS 35+37, and (B) looking toward the right bank at the same obstruction bar. Note that the bar surface slopes upward going downstream. Photographed September 1, 2005.

A.

B.

Figure B-8. (A) Perched coarse gravel and small cobble deposit created by upstream and downstream boulder ribs on right bank of the mainstem Clavey River looking upstream. Note that the deposit does not extend down to the low flow channel, and (B) the same perched deposit looking toward the right bank (flow right to left). Note that the deposit surface is flat, rather than sloping upstream or downstream. Photographed August 30, 2005.

Figure B-9. Run tail deposit of cobbles just above the stretched survey tape and on the right side of the photograph (looking downstream and toward the left bank) on the mainstem Clavey River. Photographed September 2, 2005.

Eddy Deposits (Figure B-10)

Eddy deposits typically are silt, sand, and/or small gravel depositional features deposited during late stages of falling flood limbs, in the hydraulic shadow of a large boulder or along the margin of a deep pool. These are highly mobile features. Eddy deposits can be composed of coarser sediment when formed by a big flood, though these features generally are scoured away by smaller floods.

Figure B-10A. Eddy deposit on the right bank of a pool in the mainstem Clavey River created by a prominent boulder rib; snowmelt recession streamflows of 1112 cfs on May 27, 2005

Figure B-10B. Eddy deposit on the right bank of a pool in the mainstem Clavey River created by a prominent boulder rib; snowmelt recession streamflows of 406 cfs on June 08, 2005

Figure B-10C. Eddy deposit on the right bank of a pool in the mainstem Clavey River created by a prominent boulder rib; snowmelt recession streamflows of 184 cfs on July 8, 2005

Depositional Features in the Clavey River Landscape

While a classification scheme for depositional features is a handy tool, it does not convey the fascinating morphological diversity and dynamic nature of steep boulder-bedrock Sierra Nevada mainstem channels. The best way to appreciate this dynamic diversity is to walk and observe it at various streamflows, keeping in mind the several concepts just discussed (e.g., that bedrock rivers have many depositional features). Although a poor substitute for firsthand observation, panoramic ground photos may help the reader capture some of this rich diversity. Ultimately the broad goal of pulse flows is to restore and protect this morphological diversity.

Wider and less steep channel segments tend to have more diverse and larger depositional features. A good visual perspective of nested depositional features can be seen in the panoramic photograph of the Clavey River mainstem looking downstream at cross section XS 35+67 (Figure B-11). The channel width in the foreground (upstream of the cross section tape) narrows downstream to the prominent dark gray bedrock outcrop (with the appearance of a giant boulder) on the left bank and light gray bedrock outcrop on the right bank visible within the riparian trees. Below this channel constriction (relative to the width upstream) the downstream channel appears to drop off sharply. One large boulder rib connects the opposing bedrock outcrops, while another upstream rib of smaller boulders angles upstream toward the right bank. Just upstream of the photograph is another boulder rib. The channel slope above the constriction is gentler than downstream, giving the appearance of the channel dropping off.

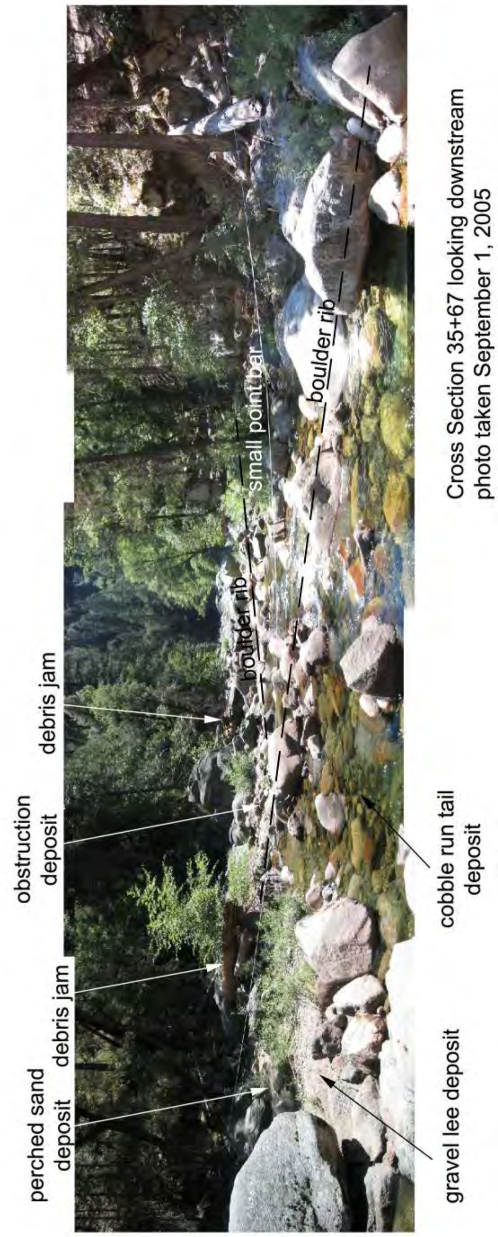

Figure B-11. Panoramic photograph of the Clavey River mainstem looking downstream at cross section XS 35+67

This constriction functions as a primary hydraulic control. The boulder ribs upstream composed of smaller boulders are influenced by the primary control below, and in turn, exert a secondary hydraulic influence. Several depositional features depend on the boulder ribs: a small boulder point bar on the right bank, a small boulder/large cobble obstruction bar on the left bank, a perched sand deposit on the left bank, and a gravel/small cobble lee deposit on the left bank and right bank. Also along the left bank is a large woody debris jam, with a lee cobble bar overtopped by a deposit of sand and small gravel. Last, a cobble run tail deposit is at the cross-section's thalweg.

Appendix C
Hydrologic Analyses

Appendix C
Hydrologic Analyses

The following tables summarize the data represented in the annual hydrographs, the snowmelt hydrographs, the flood frequency curves, and the snowmelt recession node curves (Tables C-1 to C-5).

Table C- 1. Water year and runoff year designations (Extremely Wet, Wet, Normal, Dry, and Critically Dry) from WY1960 to WY1994 and WY2005 at the 1N01 Bridge (Clavey River near Buck Meadows, USGS Gage No. 1283500)

Water Year	Water Year Annual Yield (ac-ft)	Water Year Type	Runoff Year Yield (ac-ft) (Apr 1–Aug 30)	Runoff Year Type
1960	90,869	Dry	26,839	Dry
1961	47,130	Critically Dry	14,544	Critically Dry
1962	162,025	Normal	62,454	Normal
1963	202,282	Wet	64,928	Wet
1964	97,420	Dry	31,094	Normal
1965	283,212	Wet	65,886	Wet
1966	119,747	Normal	28,704	Dry
1967	313,949	Extremely Wet	103,104	Extremely Wet
1968	91,716	Dry	24,224	Dry
1969	397,749	Extremely Wet	124,193	Extremely Wet
1970	208,752	Wet	36,294	Normal
1971	171,878	Normal	48,815	Normal
1972	120,954	Normal	29,972	Dry
1973	207,618	Wet	72,041	Wet
1974	233,833	Wet	62,112	Normal
1975	227,570	Wet	87,999	Wet
1976	55,798	Critically Dry	13,546	Critically Dry
1977	22,457	Critically Dry	7,666	Critically Dry
1978	298,854	Extremely Wet	94,859	Extremely Wet
1979	201,584	Normal	69,512	Wet
1980	347,127	Extremely Wet	77,208	Wet
1981	83,995	Dry	28,018	Dry
1982	438,384	Extremely Wet	119,140	Extremely Wet
1983	558,244	Extremely Wet	154,052	Extremely Wet
1987	49,708	Critically Dry	14,798	Critically Dry
1988	59,549	Critically Dry	14,835	Critically Dry
1989	119,378	Normal	29,890	Dry
1990	70,260	Dry	17,580	Critically Dry
1991	90,593	Dry	38,280	Normal
1992	72,415	Dry	19,314	Critically Dry
1993	278,438	Wet	84,504	Wet
1994	62,048	Critically Dry	20,123	Dry
2005		Extremely Wet	103,132	Extremely Wet

Table C- 2. Ranked annual maximum peak flood discharges from WY1960 to WY1997 at the Buck Meadows USGS Gage No. 11283500

Water Year	Rank	Annual Peak Discharge (cfs)
1997	1	47000
1980	2	19400
1963	3	19200
1982	4	15200
1965	5	12400
1969	6	8920
1970	7	6970
2005	8	6,837
1983	9	6350
1967	10	5950
1974	11	3870
1978	12	3680
1962	13	3570
1960	14	3420
1979	15	3270
1989	16	3260
1971	17	2950
1975	18	2870
1993	19	2760
1964	20	2480
1973	21	2250
1966	22	1850
1990	23	1310
1991	24	1310
1968	25	1270
1981	26	1200
1972	27	1090
1976	28	1040
1987	29	829
1992	30	727
1961	31	576
1994	32	537
1988	33	458
1977	34	246

Table C- 3. Ranked annual maximum peak flood discharges for Cherry Creek: (1) prior to flow regulation at USGS Gage No. 11277000 Cherry Creek near Hetch Hetchy from WY1915 to WY1955, and (2) after regulation at USGS Gage No. 11277300 below Valley Dam from WY1957 to WY2005

Annual Maximum Floods, Pre-dam ranked data Cherry Creek Near Hetch Hetchy (USGS gaging station #11277000)		
Date of Peak	Instantaneous Peak Q	Water Year
12/11/1937	18,100	1938
11/18/1950	13,400	1951
12/3/1941	10,100	1942
10/30/1945	9,640	1946
6/16/1929	7,750	1929
2/2/1945	7,660	1945
3/25/1928	7,000	1928
11/18/1942	6,380	1943
10/28/1924	5,800	1925
3/9/1954	5,650	1954
6/7/1936	5,400	1936
3/26/1940	5,200	1940
4/27/1953	5,100	1953
1/17/1916	4,800	1916
6/2/1922	4,400	1922
6/8/1915	3,990	1915
5/23/1941	3,960	1941
6/5/1952	3,850	1952
6/10/1921	3,840	1921
6/9/1917	3,800	1917
5/16/1927	3,640	1927
6/16/1937	3,640	1937
5/28/1919	3,550	1919
5/19/1920	3,550	1920
6/6/1935	3,400	1935
6/16/1923	3,370	1923
5/31/1950	3,360	1950
5/14/1949	3,310	1949
5/14/1944	3,280	1944
5/26/1948	3,200	1948
11/23/1946	3,170	1947
5/30/1933	3,020	1933
6/11/1932	2,940	1932
5/4/1926	2,790	1926
5/21/1955	2,790	1955
6/13/1918	2,740	1918
5/13/1931	2,500	1931

Annual Maximum Floods, Post-dam ranked data Cherry Creek below Valley Dam (USGS gaging station #11277300)		
Year	Instantaneous Peak Q	Water Year
1996	5,120	1996
2004	4,930	2004
1974	4,210	1974
1958	3,830	1958
1982	3,530	1982
1983	3,410	1983
2005	3,250	2005
1995	3,080	1995
1997	2,430	1997
1957	2,120	1957
1959	1,820	1959
1960	1,820	1960
1980	1,650	1980
1989	1,510	1989
1998	1,500	1998
2003	1,490	2003
1968	1,390	1968
1999	1,240	1999
1967	1,180	1967
1969	990	1969
1963	975	1963
2002	925	2002
1977	912	1977
1965	855	1965
1978	822	1978
2000	711	2000
1986	706	1986
1961	446	1961
1987	424	1987
1988	415	1988
1970	181	1970
1993	73	1993
1975	67	1975
1984	62	1984
1979	58	1979
1972	46	1972
1962	44	1962

Annual Maximum Floods, Pre-dam ranked data Cherry Creek Near Hetch Hetchy (USGS gaging station #11277000)		
Date of Peak	**Instantaneous Peak Q**	**Water Year**
10/15/1938	2,390	1939
5/19/1930	2,150	1930
12/13/1933	1,850	1934
5/1/1924	1,500	1924

Annual Maximum Floods, Post-dam ranked data Cherry Creek below Valley Dam (USGS gaging station #11277300)		
Year	**Instantaneous Peak Q**	**Water Year**
1991	43	1991
1981	37	1981
1985	31	1985
1976	28	1976
1992	25	1992
1990	22	1990
1964	20	1964
1973	20	1973
1966	18	1966
1971	18	1971
2001	18	2001
1994	17	1994

Table C- 4. Ranked peak daily average snowmelt streamflows from highest to lowest and ranked annual snowmelt peaks by date from earliest to latest in the snowmelt hydrograph period

Runoff Year	Peak Daily Average Snowmelt Streamflow (cfs) Ranked by Magnitude	Calendar Day	Peak Daily Average Snowmelt Streamflow (cfs) Sorted by Calendar Day
1982	10,300	1-Apr	775
1995	5,840	1-Apr	533
2005	4,395	1-Apr	1,670
1983	3,230	4-Apr	392
1967	2,960	7-Apr	670
1978	2,630	7-Apr	875
1996	2,623	11-Apr	10,300
1969	2,240	13-Apr	575
1975	2,200	15-Apr	1,380
1998	2,155	15-Apr	1,642
1963	1,940	15-Apr	1,564
1973	1,700	19-Apr	429
1974	1,670	19-Apr	1,146
1979	1,650	24-Apr	769
1984	1,642	25-Apr	2,630
1985	1,564	26-Apr	400
1993	1,530	27-Apr	1,650
1965	1,470	29-Apr	1,470
1980	1,440	30-Apr	396
1962	1,380	30-Apr	1,530

Runoff Year	Peak Daily Average Snowmelt Streamflow (cfs) Ranked by Magnitude	Calendar Day	Peak Daily Average Snowmelt Streamflow (cfs) Sorted by Calendar Day
1999	1,305	1-May	5,840
1986	1,209	2-May	583
1997	1,146	4-May	1,440
1991	923	8-May	923
1989	875	9-May	1,940
1971	837	9-May	2,240
1966	775	10-May	489
1981	769	13-May	644
1970	732	15-May	837
1960	670	16-May	4,395
1964	644	17-May	732
1972	583	17-May	1,700
1992	575	18-May	2,200
1968	533	22-May	2,960
1976	489	23-May	2,623
1994	429	24-May	197
1990	424	28-May	1,209
1988	400	28-May	424
1987	396	28-May	1,305
1961	392	29-May	3,230
1977	197	6-Jun	2,155

Table C- 5. Annual snowmelt recession nodes for the Clavey River at Buck Meadows in ranked RY types

Runoff Year	RY Class	Snowmelt Recession Node (cfs)	Day of Node
1983	Extremely Wet	410	17-Jul
1969	Extremely Wet	400	28-Jun
1982	Extremely Wet	400	4-Jun
1998	Extremely Wet	320	20-Jul
2005	Extremely Wet	500	16-Jun
1967	Extremely Wet	330	10-Jul
1978	Extremely Wet	390	27-Jun
1993	Extremely Wet	390	21-Jun
1975	Wet	400	25-Jun
1996	Wet	325	16-Jun
1980	Wet	320	5-Jul
1986	Wet	300	23-Jun
1973	Wet	300	14-Jun
1979	Wet	310	12-Jun
1984	Wet	315	14-Jul
1999	Wet	300	27-Jun
1974	Above Normal	225	17-Jun
1965	Above Normal	325	17-Jun
1963	Above Normal	260	19-Jun
1962	Above Normal	280	20-Jun
1971	Below Normal	240	24-Jun
1985	Below Normal	225	21-May
1997	Below Normal	235	20-May
1970	Below Normal	220	6-Jun
1991	Dry	200	14-Jun
1989	Dry	255	19-May
1966	Dry	200	23-May
1972	Dry	210	23-May
1964	Dry	210	14-Jun
1960	Dry	200	21-May
1981	Dry	190	1-Jun
1968	Dry	180	19-May
1992	Critically Dry	125	14-May
1994	Critically Dry	100	9-Jun
1990	Critically Dry	145	7-May
1988	Critically Dry	125	25-May
1987	Critically Dry	110	16-May
1961	Critically Dry	85	31-May
1976	Critically Dry	130	15-May
1977	Critically Dry	75	2-Jun

Appendix D
Modeled Bed Mobilization Thresholds

Appendix D
Modeled Bed Mobilization Thresholds

Streamflow thresholds for mobilizing bed surfaces and initiating coarse sediment transport are fundamental to quantifying how annual hydrographs affect channel morphology in alluvial and bedrock rivers (USFWS and HVT 1999). In alluvial rivers, there is a comparatively narrow range of threshold flows that mobilizes many depositional features (e.g., 1.2-yr flood to 5-yr flood). Boulder-bedrock rivers are often erroneously assumed to be sediment transport zones lacking depositional features. Boulder-bedrock rivers nearly always exhibit nested depositional features, ranging from large boulder ribs down to lee sand deposits. When assessing bed mobility on steep boulder-bedrock rivers, there is a much greater range of particle sizes (large boulders to fine sand) than in alluvial rivers, so particle sizes must be clearly targeted for predicting mobilization. Nested depositional features in a boulder-bedrock river should have a much wider range of threshold flows (e.g., 1.2-yr flood to 100-yr flood) than in alluvial channels.

Bed mobility and bedload transport thresholds in alluvial rivers have received considerable research the past 70 years, using field experiments (e.g., tracer rocks), bedload transport data (e.g., Parker et al. 1982), and analytical methods (e.g., Wiberg and Smith 1989). The overall smaller size and size range of particle sizes in alluvial rivers allow the hydraulic forces acting on these particles to be reasonably computed. With particle sizes ranging up to house-sized boulders in steep boulder-bedrock rivers, the acting forces are more complex than lift and drag forces (flow separation, particle sliding) and the hydraulics are more complex (local critical flow, standing waves). While analytical approaches have been attempted to predict bed mobilization thresholds in boulder-bedrock channels (e.g., Bathurst 1987; Carling and Tinkler 1998), the accuracy of these predictions still lags behind that of alluvial river predictions. Classification of nested controls and depositional features helped to categorize differential mobility thresholds for the mainstem Clavey River. However, a reasonably accurate analytical approach to predict bed mobilization thresholds in steep boulder-bedrock channels does not yet exist.

Several analytical approaches were explored. Carling and Tinkler (1998) summarize investigations that evaluate mobilization processes of individual large rocks via rolling (pivoting) or sliding. They generalize that large boulders tend to mobilize when the Froude number (Fr) equals 1 and the associated critical depth (Hc) is at least equal to the height of the boulder (Di). This method may apply to the largest framework particles in a nested depositional feature, but not the smaller particles nested within the larger particles. These smaller particles are variably hidden among the larger particles, such that the hydraulic forces acting upon these smaller particles are extremely variable. Analysis of sediment transport thresholds using Bathurst (1987) was also attempted for individual patches at the Cottonwood Bar and the boulder sub-reach, but Bathurst's equation was not intended to be applied to individual depositional patches, and results were unrealistic and not used in this report.

A promising method to predict mobility and scour of these smaller depositional features was developed by Barta et al. (1994), and refined by Barta et al. (2000), where the mobility threshold of smaller depositional features is estimated by: (1) the upstream or downstream obstruction height responsible for their existence, and (2) the ratio of cross-sectionally averaged shear stress to critical shear stress for the particle size of that patch. These relationships were developed from empirical data on streams smaller than the Clavey River mainstem on the east side of the Sierra Nevada, where obstruction heights were generally less than 3.2 ft high (1 m).

Barta et al. (2000) empirically measured "gravel pocket" (their term for a small local depositional feature) mobility and scour at five study sites in the eastern Sierra Nevada between 1991 and 1993. Tracer rocks, marbles, and scour chains were used to document mobility and scour of gravel pockets formed by upstream obstructions (obstruction bars), downstream obstructions (lee deposits), and surrounding obstructions, or internal deposits (perched deposits). Depositional features not associated with an obstruction (e.g., point bars) were avoided. Qualitative mobility categories were developed to describe mobilization observations: (1) negligible movement, (2) partial movement, and (3) general movement. Study site slopes ranged from 2% to nearly 12%. Particle sizes in the depositional features ranged from 13 millimeters (mm) to 56 mm. While the general slope of the Clavey River is within the range of slopes in Barta's study sites, the particle sizes of Barta's study sites are generally finer than the patches on the Clavey River.

Basic mechanisms underlying Barta's method include the following:

1. Iincreasing obstruction heights require higher cross sectionally averaged shear stresses to mobilize a gravel deposit formed by that obstruction.
2. The greater the relative shear stress, the greater deposit mobilization.
3. As obstructions get larger, cross-channel velocities play an increasing role in pocket mobilization compared to obstruction overtopping.

The relationship is illustrated graphically relating the ratio of obstruction height/D90 of the pocket gravels (X-axis) versus relative shear stress. The X-axis uses the obstruction height that most influenced the local flow and was usually the largest obstruction. Relative shear stress is the ratio of total boundary shear stress divided by the critical shear stress for the particle size of interest within the gravel deposit ($\tau b / \tau c$), where boundary shear stress is computed by:

$$\tau_b = \rho_w ghS \tag{1}$$

where: ρ_w = density of water (1000 kilograms per cubic meter [kg/m^3]), g = gravitational acceleration (9.81 m/s^2), h = local depth at the deposit, and S = energy slope.

While the equation computes local boundary shear stress, the actual boundary shear stress at that location cannot be accurately computed by this equation, and therefore, it is only used as a comparative index to the critical shear stress for a given particle of interest in a gravel deposit. Critical shear stress was computed for each particle using the methods of Wilcock (1992), assuming small bimodality in the particle size distribution:

$$\tau_c = \alpha\tau_{sm}$$
$$\tau_{sm} \approx \tau^*_c D_{50} g(\rho_s - \rho_w) \tag{2}$$

where τ_{sm} = Shields stress for the median grain size, τ^*_c= dimensionless Shields parameter for uniform particle size distribution, D_{50}= median particle size of interest, ρ_s = density of sediment (assumed to be 2650 kg/m³), and α = coefficient partially dependent on the bimodality of the particle size distribution. For rough flow, τ^*_c = 0.06, and for small bimodality particle size distributions, Wilcock (1992) recommends that α = 1.0. Substituting and simplifying, the Y-axis is computed as:

$$\text{relative shear stress} = \frac{\tau_b}{\tau_c} = \frac{hS}{0.1D_{50}} \tag{3}$$

To estimate local critical depth to initiate "general movement" as applied by Barta et al. (2000), the relative shear stress is estimated from the Barta et al. (2000) Figure 4, based on the obstruction height for a given gravel deposit. The critical depth is computed as:

$$h = \frac{\tau_b}{\tau_c}\left(\frac{0.1D_{50}}{S}\right) \tag{4}$$

To estimate the total flow to achieve critical depth at the deposit, the Hydrologic Engineering Centers River Analysis System (HEC-RAS) model is run, increasing flows until the local depth at the deposit equals the critical depth computed above.

Barta et al. (2000) also generate an equation to predict critical obstruction submergence for a given particle size. Their observations suggest that the gravel deposits, regardless of patch particle size distribution, are mobilized when the obstruction depth is between 70% and 100%. They assume 80% as a general rule of thumb for streams at the lower end of their slope range when only considering obstruction submergence factors (i.e., ignoring transverse flow and turbulence factors). As the slope of the stream increases, the size of the obstruction increases, and the influence of transverse flow and turbulence assumes a larger role in mobilizing gravel deposits. Therefore, as obstruction size increases, less submergence of the obstruction is required to mobilize gravel deposits, dropping to as little as 40% for steeper streams. Based on their Sierra Nevada data, they developed a relationship between critical obstruction depth (water depth/obstruction height) as a function of slope:

$$h^*_c = 0.8 - (3.04S - 0.015)^{(1-S)} \tag{5}$$

For a given obstruction height, the critical depth at the deposit can be computed. As done above, the HEC-RAS model is run, increasing flows until the local depth at the deposit equals the critical depth computed above.

The last method in Barta et al. (2000) that was of use is the general observation that gravel deposits were mobilized when the relative shear stress (τb/τc, where τb is the average boundary shear stress for all the deposits in the reach and τ_c is the critical shear stress for the D_{50} particle size in the pocket) is greater than 3. The critical boundary shear stress for the D_{50} is computed in Equation 2, and the boundary shear stress to mobilize the D_{50} from a given gravel deposit is computed from:

$$\tau_{bcD50} = (3)\tau_c = (3)\,\alpha\,\tau^*_c D_{50}\,g(\rho_s - \rho_w) = (3)(1.0)(0.06)D_{50}(9.81)(1650) = 2913D_{50} \tag{6}$$

The HEC-RAS model could be run to predict the flow necessary to achieve the boundary shear stress necessary to exceed three times the critical boundary shear stress for the D_{50}, where shear stress was computed using the HEC-RAS water surface slope through the respective cross section as described by Barta et al. (2000). The Barta et al. (2000) approach can be applied to many more locations than the tractive force approaches because it is not as dependent on a reasonably accurate prediction of boundary shear stress, but instead depends more on obstruction height which can be measured easily.

The Barta et al. (2000) method was applied at locations within the Cottonwood Bar sub-reach and boulder-bedrock sub-reach (Table D-1). The relationships developed by Barta et al. (2000) to predict mobility and scour were useful to estimate mobility thresholds on these smaller deposits of particles within nested depositional features. However, the plots in Barta et al. (1994) and Barta et al. (2000) are small and the raw data could not be obtained from the first author. For this project, pertinent charts from Barta et al. (2000) were scanned then fit to log paper to re-create the predicted mobility threshold relationship. Cross section, slope, obstruction height, and particle size data were collected in spring 2005 as needed to support this analysis as discussed above. The HEC-RAS model was run to predict the flow necessary to achieve the boundary shear stress necessary to exceed three times the critical boundary shear stress for the D_{50}, where shear stress was computed using the HEC-RAS water surface slope through the respective cross section, as described by Barta et al. (2000).

Table D- 1. Summary of depositional features on the Clavey River targeted for analysis using methods of Barta et al. (2000)

Cross section	Type of deposit	Obstruction used for height measurement
12+60	Obstruction	Downstream
16+33	Obstruction	Downstream (smaller)
16+33	Obstruction	Upstream (larger)
17+53	Lee	Upstream
32+10	Lee (cobble)	Upstream
32+10	Lee (small gravel)	Upstream
35+37	Lee	Upstream
35+67	Lee	Upstream
37+11	Lee	Upstream
37+39	Obstruction (center of channel)	Downstream
37+39	Lee (right bank)	Upstream

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Appendix E
Riparian Vegetation Modeling Results

Appendix E
Riparian Vegetation Modeling Results

Successful initiation along cross section XS 16+33 was possible in all sample runoff years for dusky willow and for Jepson's willow in the drier runoff years (Table E-1) at the point bar's edge and lower bar flank (i.e., close to the summer baseflow shoreline). There was no survival through the first summer higher up on this Cottonwood Bar cross section. Early establishment may have occurred in WY1971 and WY1976 for dusky willow and for Jepson's willow in WY1976 (Table E-1). Seedlings in both runoff years were likely scoured away in WY1980's 17-yr winter flood peak.

Table E- 1. Modeling results for arroyo, Jepson's, and dusky willow initiation and early establishment on XS 16+33 for RY2005 (Extremely Wet), RY1973 (Wet), RY1971 (Normal), RY1968 (Dry), and RY1976 (Critically Dry)

		RY2005 EXTREMELY WET						
		Bar Edge	*Lower Bar Flank*	*Upper Bar Flank*	*Bar Bench*	*Lower Middle Bar*	*Upper Middle Bar*	*Top Bar*
SURFACE EXPOSED DURING SEED DISPERSAL	arroyo willow	NO	NO	NO	NO	NO	YES	YES
	Jepson's willow	NO	NO	NO	NO	YES	YES	YES
	dusky willow	YES	YES	YES	YES	YES	YES	YES
SEEDS GERMINATE	arroyo willow	NO	NO	NO	NO	NO	YES	YES
	Jepson's willow	NO	NO	NO	NO	YES	YES	NO
	dusky willow	YES	YES	YES	YES	NO	NO	NO
SEEDLING SURVIVES FIRST SUMMER	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	YES	YES	NO	NO	NO	NO	NO

SEEDLING SURVIVES FIRST WINTER	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	YES	YES	NO	NO	NO	NO	NO

SEEDLING SURVIVES SECOND SNOWMELT HYDROGRAPH	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO	NO

		RY1973 WET						
		Bar Edge	***Lower Bar Flank***	***Upper Bar Flank***	***Bar Bench***	***Lower Middle Bar***	***Upper Middle Bar***	***Top Bar***
SURFACE EXPOSED DURING SEED DISPERSAL	arroyo willow	NO	NO	NO	NO	NO	YES	YES
	Jepson's willow	NO	NO	YES	YES	YES	YES	YES
	dusky willow	YES	YES	YES	YES	YES	YES	YES
SEEDS GERMINATE	arroyo willow	NO	NO	NO	NO	NO	YES	NO
	Jepson's willow	NO	NO	YES	YES	YES	NO	NO
	dusky willow	YES	YES	NO	NO	NO	NO	NO
SEEDLING SURVIVES FIRST SUMMER	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	YES	NO	NO	NO	NO	NO	NO

SEEDLING SURVIVES FIRST WINTER	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO	NO

SEEDLING SURVIVES SECOND SNOWMELT HYDROGRAPH	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO	NO

		RY1971 NORMAL						
		Bar Edge	***Lower Bar Flank***	***Upper Bar Flank***	***Bar Bench***	***Lower Middle Bar***	***Upper Middle Bar***	***Top Bar***
SURFACE EXPOSED DURING SEED DISPERSAL	arroyo willow	NO	NO	NO	NO	YES	YES	YES
	Jepson's willow	NO	NO	NO	YES	YES	YES	YES
	dusky willow	YES	YES	YES	YES	YES	YES	YES
SEEDS GERMINATE	arroyo willow	NO	NO	NO	NO	YES	NO	NO
	Jepson's willow	NO	NO	NO	YES	YES	NO	NO
	dusky willow	YES	YES	NO	NO	NO	NO	NO
SEEDLING SURVIVES FIRST SUMMER	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	YES	NO	NO	NO	NO	NO	NO

SEEDLING SURVIVES FIRST WINTER	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	YES	NO	NO	NO	NO	NO	NO

SEEDLING SURVIVES SECOND SNOWMELT HYDROGRAPH	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	YES	NO	NO	NO	NO	NO	NO

		RY1968 DRY						
		Bar Edge	***Lower Bar Flank***	***Upper Bar Flank***	***Bar Bench***	***Lower Middle Bar***	***Upper Middle Bar***	***Top Bar***
SURFACE EXPOSED DURING SEED DISPERSAL	arroyo willow	NO	NO	NO	YES	YES	YES	YES
	Jepson's willow	YES	YES	YES	YES	YES	YES	YES
	dusky willow	YES	YES	YES	YES	YES	YES	YES
SEEDS GERMINATE	arroyo willow	NO	NO	NO	YES	YES	NO	NO
	Jepson's willow	YES	YES	YES	NO	NO	NO	NO
	dusky willow	YES	NO	NO	NO	NO	NO	NO
SEEDLING SURVIVES FIRST SUMMER	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	YES	NO	NO	NO	NO	NO	NO
	dusky willow	YES	NO	NO	NO	NO	NO	NO

SEEDLING SURVIVES FIRST WINTER	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO	NO
SEEDLING SURVIVES SECOND SNOWMELT HYDROGRAPH	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO	NO

		RY1976 CRITICALLY DRY						
		Bar Edge	***Lower Bar Flank***	***Upper Bar Flank***	***Bar Bench***	***Lower Middle Bar***	***Upper Middle Bar***	***Top Bar***
SURFACE EXPOSED DURING SEED DISPERSAL	arroyo willow	NO	YES	YES	YES	YES	YES	YES
	Jepson's willow	YES	YES	YES	YES	YES	YES	YES
	dusky willow	YES	YES	YES	YES	YES	YES	YES
SEEDS GERMINATE	arroyo willow	NO	YES	YES	YES	YES	NO	NO
	Jepson's willow	YES	YES	NO	NO	NO	NO	NO
	dusky willow	YES	YES					
SEEDLING SURVIVES FIRST SUMMER	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	YES	NO	NO	NO	NO	NO	NO
	dusky willow	YES	NO	NO	NO	NO	NO	NO

SEEDLING SURVIVES FIRST WINTER	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	YES	NO	NO	NO	NO	NO	NO
	dusky willow	YES	NO	NO	NO	NO	NO	NO

SEEDLING SURVIVES SECOND SNOWMELT HYDROGRAPH	arroyo willow	NO	NO	NO	NO	NO	NO	NO
	Jepson's willow	YES	NO	NO	NO	NO	NO	NO
	dusky willow	YES	NO	NO	NO	NO	NO	NO

Successful initiation along cross section XS 32+62 occurred at several locations on this point bar for dusky willow and Jepson's willow (Table E-2). The relief of the point bar on XS 32+62 was much less than that of Cottonwood Bar, and would account for moisture being more readily available for seed germination and early growth (i.e., its bed surface is closer (in elevation) to the summer baseflow water surface than is most of the bed surface of Cottonwood Bar). Early establishment may have occurred in WY1971 and WY1976 for dusky willow and for Jepson's willow in WY1976 (Table E-2). Dusky willow seedlings originating in WY1971, and achieving early establishment entering their second winter (of WY1973), might have been scoured away in WY1973's 3-yr winter flood peak, but all seedlings would have been scoured away by WY1980's 17-yr winter flood peak.

Table E- 2. Modeling results for arroyo, Jepson's, and dusky willow initiation and early establishment on XS 32+62 for RY2005 (Extremely Wet), RY1973 (Wet), RY1971 (Normal), RY1968 (Dry), and RY1976 (Critically Dry)

		RY2005 EXTREMELY WET					
		Upper Lee deposit	***Lower Lee deposit***	***Bar Flank***	***Lower Point Bar***	***Upper Point Bar***	***Upper Bar***
SURFACE EXPOSED DURING SEED DISPERSAL	arroyo willow	NO	NO	NO	NO	NO	YES
	Jepson's willow	YES	NO	NO	NO	NO	YES
	dusky willow	YES	YES	YES	YES	YES	YES

SEEDS GERMINATE	arroyo willow	NO	NO	NO	NO	NO	YES
	Jepson's willow	YES	NO	NO	NO	NO	YES
	dusky willow	NO	YES	YES	YES	YES	NO

SEEDLING SURVIVES FIRST SUMMER	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	YES	YES	YES	NO	NO

SEEDLING SURVIVES FIRST WINTER	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO

SEEDLING SURVIVES SECOND SNOWMELT HYDROGRAPH	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO

		RY1973 WET					
		Upper Lee Deposit	***Lower Lee Deposit***	***Bar Flank***	***Lower Point Bar***	***Upper Point Bar***	***Upper Bar***
SURFACE EXPOSED DURING SEED DISPERSAL	arroyo willow	NO	NO	NO	NO	NO	YES
	Jepson's willow	YES	YES	NO	NO	YES	YES
	dusky willow	YES	YES	YES	YES	YES	YES
SEEDS GERMINATE	arroyo willow	YES	NO	NO	NO	NO	YES
	Jepson's willow	NO	YES	NO	NO	YES	NO
	dusky willow	NO	YES	YES	NO	NO	NO
SEEDLING SURVIVES FIRST SUMMER	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	YES	YES	NO	NO	NO

SEEDLING SURVIVES FIRST WINTER	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO
SEEDLING SURVIVES SECOND SNOWMELT HYDROGRAPH	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO

		RY1971 NORMAL					
		Upper Lee Deposit	***Lower Lee Deposit***	***Bar Flank***	***Lower Point Bar***	***Upper Point Bar***	***Upper Bar***
SURFACE EXPOSED DURING SEED DISPERSAL	arroyo willow	YES	NO	NO	NO	NO	YES
	Jepson's willow	YES	NO	NO	NO	NO	YES
	dusky willow	YES	YES	YES	YES	YES	YES
SEEDS GERMINATE	arroyo willow	YES	NO	NO	NO	NO	YES
	Jepson's willow	YES	NO	NO	NO	NO	YES
	dusky willow	NO	YES	YES	YES	NO	NO
SEEDLING SURVIVES FIRST SUMMER	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	YES	YES	YES	NO	NO
SEEDLING SURVIVES FIRST WINTER	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	YES	YES	NO	NO

SEEDLING SURVIVES SECOND SNOWMELT HYDROGRAPH	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	YES	YES	NO	NO

		RY1968 DRY					
		Upper Lee Deposit	***Lower Lee Deposit***	***Bar Flank***	***Lower Point Bar***	***Upper Point Bar***	***Upper Bar***
SURFACE EXPOSED DURING SEED DISPERSAL	arroyo willow	YES	NO	NO	NO	NO	YES
	Jepson's willow	YES	YES	YES	YES	YES	YES
	dusky willow	YES	YES	YES	YES	YES	YES
SEEDS GERMINATE	arroyo willow	YES	NO	NO	NO	NO	YES
	Jepson's willow	NO	YES	YES	YES	NO	NO
	dusky willow	NO	NO	YES	NO	NO	NO
SEEDLING SURVIVES FIRST SUMMER	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	YES	YES	YES	NO	NO
	dusky willow	NO	NO	YES	NO	NO	NO
SEEDLING SURVIVES FIRST WINTER	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO
SEEDLING SURVIVES SECOND SNOWMELT HYDROGRAPH	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	NO	NO	NO	NO	NO
	dusky willow	NO	NO	NO	NO	NO	NO

		RY1976 CRITICALLY DRY					
		Upper Lee Deposit	***Lower Lee Deposit***	***Bar Flank***	***Lower Point Bar***	***Upper Point Bar***	***Upper Bar***
SURFACE EXPOSED DURING SEED DISPERSAL	arroyo willow	YES	YES	NO	NO	YES	YES
	Jepson's willow	YES	YES	YES	YES	YES	YES
	dusky willow	YES	YES	YES	YES	YES	YES
SEEDS GERMINATE	arroyo willow	YES	YES	NO	NO	YES	YES
	Jepson's willow	NO	YES	YES	NO	NO	NO
	dusky willow	NO	NO	YES	NO	NO	NO
SEEDLING SURVIVES FIRST SUMMER	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	YES	YES	NO	NO	NO
	dusky willow	NO	NO	YES	NO	NO	NO
SEEDLING SURVIVES FIRST WINTER	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	YES	YES	NO	NO	NO
	dusky willow	NO	NO	YES	NO	NO	NO
SEEDLING SURVIVES SECOND SNOWMELT HYDROGRAPH	arroyo willow	NO	NO	NO	NO	NO	NO
	Jepson's willow	NO	YES	YES	NO	NO	NO
	dusky willow	NO	NO	YES	NO	NO	NO

White alders were not modeled for initiation or early establishment. Their seed release period lasts longer than a year because their seeds remain viable longer than a year. Seeds are generally rafted along debris lines following winter and snowmelt floods. Once germinated, white alder seedlings must undergo the same hurdles of desiccation and scour encountered by willows.